



PETROGRAPHIC METHODS AND CALCULATIONS

PART III

Chemical Methods and Calculations

OTHER WORKS
BY
ARTHUR HOLMES

THE AGE OF THE EARTH.

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Part III



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BY

ARTHUR HOLMES

D.SC. (LOND.), A.R.C.S., D.I.C., F.G.S., F.R.G.S.

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PREFACE.

Most of the volumes dealing with petrographic methods are almost wholly devoted to the optical properties of crystals and their application to the determination of minerals. The investigation of rocks by other methods does not appear to have received the same degree of attention, and in preparing this book I have therefore tried to produce a more evenly-balanced treatise which should penetrate the petrological domain, and not merely skirt its borderland. Adequate treatment of all the subjects involved would far exceed the limits of a reasonable book, and consequently field-work, on the geological side, and geophysical research, on the experimental, have been touched on but lightly. By giving examples of results already achieved, and directing attention to the problems and objects of petrology, an attempt has been made to animate the dry bones of practical methods with the stimulating spirit of research. The value and importance of petrographic methods in relation to industries have not been forgotten; and while exigencies of space have prevented more than passing reference to economic applications, I hope that these may prove sufficient to indicate to chemists, architects, engineers, and others, that the methods of work devised by the petrologist are competent to attack many of the problems with which they are faced, and are worthy of greater recognition than they have received in the past.

Most of the illustrations have been specially drawn for this book, though some are modified but slightly from publications to which acknowledgment is made in the text. *Figs. 38, 39 and 53* were drawn for me by my friend, Mr. A. Brammall, to whose co-operation I refer more fully below. I am indebted to my former colleague, Professor P. G. H. Boswell, for permission to reproduce *Figs. 41 to 44* from his well-known *Memoirs on Glass Sands and Refractory Sands*, on both of which I have drawn un-
stintingly for descriptions of methods and examples of results. *Figs. 62 and 63* are from my *Mozambique* papers in the *Quarterly Journal*, and are reproduced by permission of the Council of the Geological Society of London. The Plates are from photomicrographs skilfully prepared by Mr. G. S. Sweeting, of the Geology Department of the Imperial College. The index is also his work, and I wish to thank him not only for these services, but also for his general assistance during the last few weeks of the writing of the book.

The manuscript was completed in August, only a day or two before I was due to sail for Burma, and Mr. Brammall kindly undertook the arduous task of seeing the book through the press. Throughout its growth I have enjoyed the privilege of discussing with him many of the details of its subject matter, and for his untiring interest, his constructive criticism, and especially for his help in the final stages, I wish to express my gratitude.

ARTHUR HOLMES.

RANGOON,
October, 1920.

PREFATORY NOTE TO PART III.

Although this book was originally designed to cover the whole field of practical petrology, the treatment of the subject falls naturally into three divisions according as the methods described depend on (*a*) hand specimens, crushed and detrital material; (*b*) the study of thin sections, and (*c*) chemical analyses. For the convenience of students and others the book is now being issued in three such parts, which may be purchased separately. The text, as a whole, remains unaltered, except for the correction of certain errata.

Part III. deals entirely with the study of chemical analyses of minerals and rocks and the interpretation and representation by diagrams of such analyses. Though devoted mainly to igneous rocks and their problems, other types also receive attention. To simplify the calculations involved in the "norm" and other restatements of analyses, tables of molecular proportions of oxides and of percentage weights of standard minerals are appended. No descriptions of the methods adopted in analysing minerals and rocks are given, as such methods involve the whole of an important branch of inorganic chemistry on which there is already an adequate literature. This part is intended to bring out as forcibly as possible the value of chemical analyses in petrological problems and research, and will, it is hoped, appeal to the analyst as well as to those who apply the data he provides to the furtherance of their object—the study of rocks and their origins.

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PETROGRAPHIC METHODS AND CALCULATIONS

PART III

Chemical Methods and Calculations

PETROGRAPHIC METHODS AND CALCULATIONS.

PART III.

CHAPTER X.

CHEMICAL ANALYSES AND THEIR INTERPRETATION.

Chemical Analyses.

Few petrological investigations are complete without chemical analyses of at least some of the rocks that come under discussion, and particularly is this the case in the study of igneous rocks.¹ Knowledge of field-relations, mineral characters, structures and textures, and chemical composition all have their special bearing on the problems that arise, and all are necessary as a basis for the deduction of the processes concerned in the evolution of types. Problems that may seem to be purely of theoretical interest, such as the differentiation and alteration of igneous rocks, and the delimitation and significance of petrographical provinces, have also a fundamental bearing on the economic questions associated with mineral-deposits and metallogenic provinces, and none of these can be fully discussed without the aid of copious analyses. Among metamorphic rocks a critical study of chemical composition may be necessary to decide whether certain types of gneisses, granulites, and schists were originally igneous or detrital, or whether they were of composite origin. From the industrial standpoint analyses are often invaluable as a guide to the choice and use of raw materials. Under this category come sands and rocks used for glass-making, clays employed in the ceramic arts, and clays, marls and limestones used for the manufacture of cement.

To enter into a description of the modern methods adopted in analysing rocks would require a more volumin-

¹ For a general discussion of geological problems treated from the chemical side see F. W. Clarke: *The Data of Geochemistry*, U.S.G.S. Bull. 695, 1920 (earlier editions, Bull. 330, 1908, Bull. 491, 1911 and Bull. 616, 1916).

ous book than this, and it must suffice to direct the student to the leading literature of the subject:—

- W. F. HILLEBRAND: *The Analysis of Silicate and Carbonate Rocks*. U.S.G.S. Bull. 422, 1910; reprinted 1916; revised as Bull. 700, 1919.
 J. W. MELLOR: *A Treatise on Quantitative Inorganic Analysis*, London, 1913.
 W. R. SCHOELLER & A. R. POWELL: *The Analysis of Minerals and Ores of the Rarer Elements*, London, 1919.
 H. S. WASHINGTON: *Manual of the Chemical Analysis of Rocks*, 3rd Ed. revised, New York and London, 1919.

First-class rock-analyses are generally made only by professional chemists who have specialised in that branch of their subject. Every petrologist should, however, be able to make at least a moderately good analysis for himself, and advanced courses in petrology should provide practice in some of the more important methods and thus afford students an opportunity of appreciating the nature of the task.

The Major and Minor Constituents of Rocks.

The constituents to be determined in an analysis naturally depend on the nature of the rock to be analysed. Consideration of the dominant chemical characters of the chief rock-forming minerals at once indicates nine constituents that in igneous rocks must always be determined as an irreducible minimum. These are as follows:—

- | | |
|---|---|
| SiO ₂ | in quartz, other forms of silica, and all silicate-minerals; |
| Al ₂ O ₃ | in feldspars, feldspathoids, zeolites, micas, clay-minerals and many other alumino-silicate minerals; |
| Fe ₂ O ₃ }
FeO } | in biotite, pyroxenes, amphiboles, chlorites, iron-ores, etc.; |
| MgO | in biotite, pyroxenes, amphiboles, chlorites, olivine, serpentine, etc.; |
| CaO | in plagioclase, zeolites, pyroxenes, amphiboles, melilite, calcite and dolomite; |

- Na₂O in feldspars, feldspathoids, zeolites, soda-pyroxenes and soda-amphiboles;
 K₂O in potash-feldspars, leucite and micas;
 H₂O in zeolites, micas, clay-minerals, chlorites, serpentine, limonite, rock-glasses, etc.
 It is usual to distinguish *hygroscopic* water liberated at just over the boiling point (H₂O—, or more precisely H₂O at 105°C. or H₂O at 110°C.) from *combined* water liberated completely at a red heat (H₂O+, or H₂O above 110°C.).

In addition to the above, certain other constituents may be of essential importance in particular rocks:—

- CO₂ in limestones, dolomites, ironstones, crystalline limestones and rocks rich in carbonate-minerals generally.
 TiO₂ in rocks containing ilmenite, rutile, sphene, titan-augite and other titaniferous minerals.
 P₂O₅ in phosphorites and rocks rich in apatite.

Even in igneous rocks these three constituents may sometimes be more abundant than certain of the recognised "major" oxides. Recent work has shown, for example, that titanium-dioxide is far more abundantly and widely distributed than was formerly supposed to be the case, and in rocks of basaltic composition particularly its determination should by no means be neglected.¹ This fact is of importance, too, in relation to the determination of alumina. Unfortunately, there is no direct method of separating aluminium hydroxide from the other materials which are precipitated with it; and as it is necessarily determined by difference, it follows that if TiO₂ and P₂O₅ (also ZrO₂, Cr₂O₃ and V₂O₃) are not separately determined they will all appear in the recorded amount for "Al₂O₃," giving too high a result for the latter.

¹ A. Holmes & H. F. Harwood: "The Basaltic Rocks of the Arctic Region," *Min. Mag.*, xviii, 1918, pp. 215-18.

Microscopic examination of the rock to be analysed should, of course, precede the work of analysis, and this procedure will rarely fail to disclose any special mineralogical features that may be present. Glassy rocks may not provide preliminary evidence of the kind required as a guide to analysis, but for this very reason an analysis is the more necessary. An instructive incident in the author's experience is worth recording in this connection : a pumiceous rock from Mozambique gave little microscopic evidence of its nature, but the specific gravity and the presence of rare microlites of andesine suggested that it was probably an andesite-glass. A measurement of the radium-content, however, revealed a value surprisingly large for an alleged andesite-glass, and it was therefore deemed advisable to make an analysis. The work was thoroughly justified by the results obtained, for they showed that the rock was a tephritic glass of composition and significance very different from what had been originally assumed. This incident also illustrates the value of knowing broadly the common associations of the rarer constituents. To the consideration of these we may now turn.

The presence of certain minor and accessory minerals suggests other constituents to be determined in addition to the dozen already mentioned :—

- ZrO₂ in zircon ;
- SO₃ in nosean, hauyne, gypsum, etc. ;
- S in pyrite, pyrrhotite and other sulphides ;
- Cl in sodalite, chlor-apatite, and scapolite ;
- F in topaz, fluorite, fluor-apatite, certain micas, etc. ;
- B₂O₃ in tourmaline.

Careful and complete chemical analyses of igneous rocks, supported by mineral associations and the genetic relationships of certain types of ore-deposits to certain types of intrusions, have shown that the distribution of many of the rarer elements is not haphazard. Some of

the elements alluded to are found most abundantly in rocks rich in silica and alkalis, while others are more characteristic of rocks poor in silica and rich in lime, magnesia or iron-oxides. It is well known, for example, that cassiterite and the fluorine-bearing minerals are practically confined to rocks of the first group, while nickel-ores, platinum and chromite are restricted to those of the second. Washington has discussed such associations as completely as available data allow,¹ and in the following table his conclusions are summarised.

THE ASSOCIATIONS OF THE MINOR ELEMENTS IN IGNEOUS ROCKS.

<i>Minerals.</i>	<i>Rare Elements.</i>	<i>Chemical Characters of Igneous Rocks.</i>	<i>Rare Elements.</i>	<i>Minerals.</i>
Molybdenite Wolfram ... Galena ... Blende ... Tourmaline	Mo W Pb Zn B	Generally rich in Silica (over-saturated), <i>e.g.</i> Granites and Pegmatites	Potash dominant	Ba Hyalophane
			Alkali-rich; Soda dominant	Li Be or Gl Ce Y Th Ur Zr Sn F
				Lepidolite Spodumene Alk.-tourmaline Beryl Monazite Xenotime Thorite Uraninite Zircon Eudialyte Cassiterite Fluorite Topaz
Pyrite, Pyrrhotite and other Sulphides In Pyroxenes and Amphiboles Sulphides	S Mn Cu	Generally poor in Silica (under-saturated), <i>e.g.</i> Gabbros, Norites and Peridotites	Alkali-rich	Cl SO ₃ Sodalite Hauyne
			Calcic	P Cr Apatite Chromite
			Ferruginous	Ti V Ilmenite Titan-augite In Pyroxenes and Amphiboles
			Magnesian	Ni & Co Cr Ni Pt In Pyroxenes and Pyrrhotite Chromite In Olivine Platinum

In the middle column rock-types are divided into two main groups, and these in turn are subdivided according to noteworthy chemical characteristics. On the left are given the elements (and the chief minerals in which they occur) associated in a general way with the two chief groups; and on the right those associated more particularly with each of the subdivisions.

Statement of Chemical Analyses.

The constituents of rocks are expressed as a rule as oxides, sulphur (in sulphides), chlorine and fluorine being the chief exceptions. The various types of oxides in terms of which results are stated are as follows :—

R_2O_6	R_2O_5	R_2O_4	R_2O_3	R_2O_2	R_2O	R_2
				FeO		
				MnO		
		SiO ₂	Al ₂ O ₃	NiO	K ₂ O	S
SO ₃	P ₂ O ₅	TiO ₂	Fe ₂ O ₃	CoO	Na ₂ O	Cl
		ZrO ₂	Cr ₂ O ₃	MgO	Li ₂ O	F
		CO ₂	V ₂ O ₅	CaO	H ₂ O	
				SrO		
				BaO		

An analysis could be stated in terms of elements throughout, but it is much more convenient—as universal usage indicates—to adopt basic oxides and acidic radicles as the units of expression. It is not, however, desirable to record analyses in the order set forth above. Unfortunately there has been considerable diversity in the order of statement adopted. Washington has discussed the question in detail, and the following paragraphs are quoted directly from his *Chemical Analysis of Rocks*, 1919, p. 22 :—

“ This lack of uniformity is to be deplored, as it is not only extremely apt to lead to error in copying analyses, the order of statement of which is unfamiliar, but it also renders needlessly difficult the comparison of two or more analyses tabulated according to different systems.

“ Some years ago it was proposed¹ that petrographers and

¹ H. S. Washington : *Am. Journ. Sci.*, x, 1900, p. 59.

chemists follow a definite and uniform plan in the statement of the analyses of rocks, and the order then suggested with the reasons for its adoption are briefly given here. . . .

"The general foundation for the order proposed is that analyses of rocks are intended primarily for the benefit of petrographers and petrologists, so that an arrangement along analytical or strictly chemical lines is neither advantageous nor appropriate. To them the eight oxides, SiO_2 , Al_2O_3 , Fe_2O_3 , FeO , MgO , CaO , Na_2O , and K_2O , which are present in preponderating amount in the vast majority of rocks, are, and must always remain, of prime importance. H_2O and CO_2 , which are often present to a very notable extent, are of value as measures of the freshness of the rock. The other constituents, while of varying interest, are usually present in small or minute quantities, and influence the character of a rock only to a limited extent. . . .

"By putting the eight main oxides together and at the head, the general character of the rock may be seen at a glance. Furthermore, whether an analysis is complete or incomplete, these oxides are always in the same relative position, and, as they are (or should be) determined in every case, the eye finds them without trouble, thus greatly facilitating comparison and study."

The order suggested is as follows:—

SiO_2 chief acid radicle and most abundant constituent,

Al_2O_3 commonly associated with silica.

Fe_2O_3 commonly associated with alumina.

FeO } occur together in ferromagnesian minerals.
 MgO }

CaO occurs in both mafic and felsic minerals.

Na_2O associated with both lime and potash.

K_2O associated with water in micas.

$\text{H}_2\text{O}+$	combined water	$\left\{ \begin{array}{l} \text{connected by a} \\ \text{bracket these three} \\ \text{constitute "loss on} \\ \text{ignition."} \end{array} \right.$
$\text{H}_2\text{O}-$	hygroscopic water	
CO_2	often indicates alteration	

The remaining constituents follow in the order:—

TiO_2 , ZrO_2 , P_2O_5 , B_2O_3 , SO_3 , Cl , F , S ,
 Cr_2O_3 , V_2O_5 , MnO , NiO , CoO , BaO , SrO , Li_2O ,

the minor acid radicles being followed by the subordinate metallic oxides.

The desirability of following a standardised order has become greater than ever since the publication of Washington's *Chemical Analyses of Igneous Rocks* (1884-1913).¹ This invaluable work contains 8,602 analyses, and as the minor constituents most commonly determined are TiO_2 , P_2O_5 , and MnO , these three are placed after H_2O to facilitate tabulation and comparison. Any additional constituents are then placed in a separate column in the standard order. Ignoring the less-commonly determined constituents the statement of analyses advocated follows the order illustrated in the adjoining table which gives various regional averages for igneous rocks.

	A.	B.	C.	D.
SiO_2 ...	58.98	58.24	60.47	61.64
Al_2O_3 ...	15.41	15.80	15.07	15.71
Fe_2O_3 ...	4.78	3.33	2.68	2.91
FeO ...	2.70	3.87	3.50	3.25
MgO ...	3.71	3.84	3.85	2.97
CaO ...	4.83	5.22	4.88	5.06
Na_2O ...	3.18	3.91	3.41	3.40
K_2O ...	2.77	3.16	3.03	2.65
$\text{H}_2\text{O}+$...	2.17	1.43	1.44	1.26
$\text{H}_2\text{O}-$...		0.36	0.48	
TiO_2 ...	0.52	1.04	0.80	0.73
P_2O_5 ...	0.21	0.37	0.29	0.26
MnO ...	0.41	0.43	0.10	0.16
Totals	99.67	101.00	100.00	100.00

A.—Average of 536 British rocks. A. Harker.

B.—World-average (1,811 rocks). H. S. Washington.

C.—World-average. F. W. Clarke.

D.—Average based on the relative estimated proportions of different types of igneous rocks combined with their respective average compositions. A. Knopf: *Journ. Geol.*, xxiv, 1916, p. 620.

¹ U.S.G.S. *Prof. Pap.* 99, 1917.

Calculation of Chemical Composition.

If the chemical composition of the minerals of a rock and their respective percentages by weight are known, then the composition of the rock can readily be calculated. The percentages of the minerals may be known from—

(a) Actual separation and weighing, or

(b) Application of the Delesse-Rosiwal method of micrometric analysis combined with a knowledge of the respective specific gravities of the minerals.

The exact composition of the minerals in any particular case is not always easily ascertained, unless, of course, they have been separately analysed. In some cases the theoretical composition may be assumed with little risk of serious error, but in others—*e.g.*, most pyroxenes, amphiboles, micas and other complex solid solutions of variable composition—the safest method is to assume that they have approximately the composition of optically similar minerals which have been separated from similar types of rocks and analysed.

At the present time the correlation of optical characters with chemical composition is far from complete in many groups of minerals, but data is steadily accumulating. It is highly desirable that complete and accurate analyses of rock-forming minerals should be accompanied by records of optical properties, together with careful descriptions of the rock-types from which the minerals have in each case been separated. Conversely, optical studies should be accompanied by chemical analyses. If this double line of research were always followed the results of correlation would rapidly become of fundamental petrographic importance. Optical records alone, or chemical analyses alone, have but a limited value for the petrologist, whereas the combination places in his hands data of far superior significance, on the importance of which insistence cannot be too strongly placed.

However, if appropriate analyses can be chosen from existing records, a fairly good idea of the composition of a rock can often be gained by a simple calculation.¹

Let the minerals of the rock be represented by

1, 2, 3.....etc.,

and their percentages in the rock by p_1, p_2, p_3etc.

Let the percentages of the constituents of the mineral 1 be represented by a_1, b_1, c_1 ... etc.,

those of mineral 2 by a_2, b_2, c_2etc.,

those of mineral 3 by a_3, b_3, c_3etc.,

where $a = \text{SiO}_2$; $b = \text{Al}_2\text{O}_3$; $c = \text{Fe}_2\text{O}_3$etc.

Then the percentages of the various constituents of the rock are as follows:—

Constituents.	Minerals.			Composition of Rock.
	1.	2.	3.	
100 SiO_2	$= a_1 p_1$	$+ a_2 p_2$	$+ a_3 p_3 + \dots \text{etc.}$	$= \Sigma a p.$
100 Al_2O_3	$= b_1 p_1$	$+ b_2 p_2$	$+ b_3 p_3 + \dots \text{etc.}$	$= \Sigma b p$
100 Fe_2O_3	$= c_1 p_1$	$+ c_2 p_2$	$+ c_3 p_3 + \dots \text{etc.}$	$= \Sigma c p.$
100 FeO	$= d_1 p_1$	$+ d_2 p_2$	$+ d_3 p_3 + \dots \text{etc.}$	$= \Sigma d p.$
100 MgO	$= e_1 p_1$	$+ e_2 p_2$	$+ e_3 p_3 + \dots \text{etc.}$	$= \Sigma e p.$
100 CaO	$= f_1 p_1$	$+ f_2 p_2$	$+ f_3 p_3 + \dots \text{etc.}$	$= \Sigma f p.$
100 Na_2O	$= g_1 p_1$	$+ g_2 p_2$	$+ g_3 p_3 + \dots \text{etc.}$	$= \Sigma g p.$
100 K_2O	$= h_1 p_1$	$+ h_2 p_2$	$+ h_3 p_3 + \dots \text{etc.}$	$= \Sigma h p.$

and so on for other constituents.

Expressed in words the calculation may be described thus: each item of the analysis of mineral 1 is multiplied by the percentage (by weight) of mineral 1 in the rock. Similarly each item of mineral 2 is multiplied by the percentage of mineral 2, and so on for each of the minerals. Then the sum of the series of figures so obtained for silica

¹ For published examples see J. W. Sollas: *Q.J.G.S.*, and G. W. Tyrrell: *Q.J.G.S.*, lxxii, 1916-17, pp. 103, 110.

(divided by 100) gives the percentage of silica in the rock; the sum of the series for alumina (divided by 100) gives the required percentage for alumina, and so on for the other constituents.

Shap Granite.

As an example of the method showing the degree of concordance between calculated and actual analyses, the "light" variety of Shap granite may be taken. By measurements on polished slabs and by actual separation of porphyritic crystals and groundmass, the proportion of phenocrysts was found to be 20 per cent. (see p. 317). By measurements on thin sections, checked by separations made with bromoform, the constituents of the groundmass were found to be as follows :—

Quartz	...	...	24.4	per cent. by weight.
Oligoclase	...	...	33.6	" "
Orthoclase	...	...	16.2	" "
Biotite	...	...	5.8	" "
				—
Total	...	...	80.0	
				—

The composition of the felspar phenocrysts is known from an analysis by J. B. Cohen,¹ and that of the orthoclase in the groundmass may be taken as the same. The theoretical composition of oligoclase corresponding to $Ab_{75}An_{25}$ is assumed, the formula adopted being deduced from the average refractive index of the mineral itself. Quartz presents no difficulty, and for biotite the composition taken is that of a similar biotite² from Donegal granite—a type of granite similar in turn to that under considera-

¹ A. Harker & J. E. Marr: *Q.J.G.S.*, xlvii, 1891, p. 278.

² C. Hintze: *Handbuch der Mineralogie*, Bd. II, 1897, Analysis LXVII, p. 582.

tion. The accessory minerals are neglected for the purpose of this calculation, as they are included in the minerals listed above and the analysis with which the results are to be compared is itself incomplete as regards minor constituents.

DATA FOR CALCULATION OF CHEMICAL ANALYSIS OF SHAP GRANITE.

<i>Constituents.</i>	<i>Orthoclase.</i>	<i>Oligoclase.</i>	<i>Quartz.</i>	<i>Biotite.</i>
SiO ₂ ...	65.41	61.9	100.0	31.60
Al ₂ O ₃ ...	18.97	24.1	—	19.68
Fe ₂ O ₃ ...	—	—	—	23.35
FeO ...	0.51	—	—	4.04
MgO ...	0.01	—	—	7.03
CaO ...	0.73	5.3	—	0.45
Na ₂ O ...	2.15	8.7	—	0.74
K ₂ O ...	11.23	—	—	3.90
H ₂ O ...	—	—	—	8.68
MnO ...	Trace	—	—	1.20
Totals ...	99.01	100.00	100.0	100.67
<i>Percentage of Mineral in Rock.</i> }	36.2	33.6	24.4	5.8
<i>Constituents.</i>	<i>Orthoclase × 36.2 per cent.</i>	<i>Oligoclase × 33.6 per cent.</i>	<i>Quartz × 24.4 per cent.</i>	<i>Biotite × 5.8 per cent.</i>
SiO ₂ ...	23.68	20.80	24.40	1.83
Al ₂ O ₃ ...	6.87	8.09	—	1.14
Fe ₂ O ₃ ...	—	—	—	1.35
FeO ...	0.18	—	—	0.23
MgO ...	—	—	—	0.41
CaO ...	0.26	1.78	—	0.03
Na ₂ O ...	0.78	2.93	—	0.04
K ₂ O ...	4.07	—	—	0.23
H ₂ O ...	—	—	—	0.50
MnO ...	—	—	—	0.07
Totals ...	35.84	33.60	24.40	5.83

The figures finally obtained by adding the rows in the lower part of the preceding table are given below :—

<i>Constituents.</i>	<i>Analysis by J. B. Cohen.</i>	<i>Calculated Composition.</i>	<i>Mineral Composition.</i>
SiO ₂ ...	68.55	70.71	Porphyritic Ortho-
Al ₂ O ₃ ...	16.21	16.10	class ... 20.0
Fe ₂ O ₃ ...	2.26	1.35	Groundmass-Ortho-
FeO ...	n.d.	0.41	class ... 16.2
MgO ...	1.04	0.41	Total Orthoclase ... 36.2
CaO ...	2.40	2.07	Oligoclase ... 33.6
Na ₂ O ...	4.08	3.75	Quartz ... 24.4
K ₂ O ...	4.14	4.30	Biotite ... 5.8
H ₂ O ...	n.d.	0.50	Total ... 100.0
MnO ...	0.45	0.07	
Totals...	<u>99.13</u>	<u>99.67</u>	Average Specific Gravity ... 2.66

It will be seen that the agreement between calculated and actual composition is reasonably good. The slight excess of silica in the calculated result may be due to the figure for quartz being somewhat high, and the deficiency of iron-oxides and magnesia to the figure for biotite being too low. In any case discrepancies are bound to occur, if for no other reason than that the specimen chemically analysed was not that mineralogically analysed.

Molecular Proportions.

In order to bring out the significance of an analysis more clearly than is possible from inspection of a list of oxides, it is often convenient to recalculate the analysis in terms of compounds corresponding as closely as possible to the minerals and isomorphous molecules actually present in the material analysed. For example, an analysis of a soda-lime felspar would show SiO₂, Al₂O₃, CaO, and Na₂O as the dominant constituents, with K₂O in smaller amount, and various non-essential constituents representing inclusions in or possibly alteration-products of the mineral. If, instead of the list of oxides, we can appropriately combine the items and give percentages of *anorthite* (corresponding to CaO), *albite* (corresponding to

Na_2O), and *orthoclase* (corresponding to K_2O isomorphously replacing Na_2O), we shall have expressed the same chemical data in a far more illuminating way.

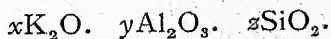
It would, of course, be possible to carry out the calculation by a straightforward but cumbersome arithmetical process, if one knew the percentage composition of each of the mineral-molecules mentioned. However, a much neater method, involving a knowledge only of molecular weights, is generally adopted, and a simple example illustrating this method is worked out in the following section. As a first step the percentages are converted into *molecular proportions*, and for the moment it will be convenient to discuss this conversion before proceeding further.

An accurate analysis of pure orthoclase would give results differing little, if at all, from the following :—

SiO_2	...	...	64.74 per cent.
Al_2O_3	...	...	18.35 „
K_2O}	...	...	16.91 „

In order to determine the empirical formula for orthoclase we require to know the numerical ratio of the “molecules” of K_2O to those of Al_2O_3 , and the ratio of those of Al_2O_3 to those of SiO_2 . Now in a molecular formula the symbol K_2O does not represent only the constituents of the material potash; it also implies an amount of potash proportional to the molecular weight of potash. Thus, K_2O represents 94 parts of potash; Al_2O_3 102 parts of alumina; and SiO_2 60 parts of silica.

Let us suppose the formula for orthoclase is



We require, then, to determine the ratio $x : y : z$.

Evidently

$$\begin{aligned} x\text{K}_2\text{O} &= 94x \propto 16.91 \\ y\text{Al}_2\text{O}_3 &= 102y \propto 18.35 \\ z\text{SiO}_2 &= 60z \propto 64.74 \end{aligned}$$

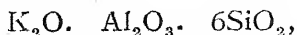
whence,

$$x \propto \frac{16.91}{94} \text{ i.e. } 0.180$$

$$y \propto \frac{18.35}{102} \text{ i.e. } 0.180$$

$$z \propto \frac{64.74}{60} \text{ i.e. } 1.079, \text{ or } 6 \times 0.1798$$

Clearly $x : y : z = 1 : 1 : 6$, and the required formula is therefore



which may also be expressed in its simplest form as KAlSi_3O_8 .

The figures obtained for x , y and z are called *molecular proportions*, *molecular ratios*, or *molecular numbers*. The latter term, adopted by Washington, should be avoided, as it has already been used by physicists in a quite different sense. The term *molecular proportion* is not technically sound, but as it has most generally been used no misconception need arise by adopting it here.¹

The molecular proportion is, then, the number obtained by dividing the percentage of any constituent of a rock or mineral by the molecular weight of that constituent. Conversely, the molecular proportion multiplied by the respective molecular weight gives the percentage of the constituent.

$$\text{Molecular proportion} = \frac{\text{Percentage}}{\text{Molecular weight.}}$$

$$\text{Percentage} = \text{Molecular proportion} \times \text{Molecular weight.}$$

Tables have been published by J. F. Kemp and others² which greatly reduce the arithmetical work

¹ In referring to molecular proportions, not as numbers, but as representing a *quantity* of some constituent, it is usual to speak of the *molecular amount*, or, briefly, of the *amount*.

² J. F. Kemp: *The School of Mines Quarterly*, xxii, pp. 82-88; reprinted in *Handbook of Rocks*, 1918, p. 171.

C. I. P. W.: *Quantitative Classification of Igneous Rocks*, 1903, pp. 237-259.

G. I. Finlay: *Introduction to the Study of Igneous Rocks*, 1913, pp. 194-221.

H. S. Washington: *Chemical Analyses of Igneous Rocks*; U.S.G.S. Prof. Pap. 99, 1917, pp. 1166-1180.

involved in recasting analyses. One set of these gives the molecular proportions for the percentages of the various oxides, etc., listed in analyses. Another set gives the percentages corresponding to the molecular proportions of the chief mineral compounds into which it is customary to combine the oxides, etc. The various divisions and multiplications are thus already worked out, and any required result can be found at once by reference to the appropriate table. Abbreviated tables of the kind described have been reproduced in an Appendix to this book, sufficient data being given to simplify calculations without taking up undue space.

Felspar from Rhomb-porphyry, Sweden.

We may now proceed to recast an actual analysis, and as a simple and instructive example the potash-oligoclase from a Swedish rhomb-porphyry may be taken.¹ The analysis and the molecular proportions of the oxides are as follows :—

Constituents.	Percentages.	Mol. Weights.	Mol. Props.
SiO ₂	63.00	60	1.0500
Al ₂ O ₃	22.50	102	0.2206
Fe ₂ O ₃	0.91	160	0.0057
MgO	0.08	40	0.0020
CaO	3.56	56	0.0636
Na ₂ O	8.54	62	0.1384
K ₂ O	1.44	94	0.0153
H ₂ O	0.32	18	0.0178
TiO ₂	0.10	80	0.0120

100.45

It is in accord with our knowledge of the constitution of felspars to regard this example as a solid solution of interlocking molecules of—

Orthoclase, K₂O. Al₂O₃. 6SiO₂, (mol. wt.=556),
 Albite, Na₂O. Al₂O₃. 6SiO₂, (mol. wt.=524),
 and Anorthite, CaO. Al₂O₃. 2SiO₂. (mol. wt.=278).

¹ P. Quensel : *Bull. Geol. Inst. Upsala*, xvi, 1918, p. 10.

The small content of Fe_2O_3 and TiO_2 probably represents inclusions of a titaniferous iron-ore; the MgO may also represent inclusions, but the amount is so small that, with the H_2O , it may be ignored for the purposes of the calculation.

The amount of *orthoclase* is fixed by that of K_2O , 0.0153, an equal amount of Al_2O_3 being required, and six times that amount of SiO_2 .

Similarly the amount of *albite* is fixed by that of Na_2O , 0.1384, and again an equal amount of Al_2O_3 is required and six times that amount of SiO_2 .

Before proceeding to build up *anorthite* it is necessary to ascertain whether the residual molecular amount of Al_2O_3 is sufficient to satisfy the amount of CaO . The balance of Al_2O_3 is 0.0669, and consequently the whole of the CaO , 0.0636 may be used for anorthite, the same amount of Al_2O_3 being required, as before, but only twice that amount of SiO_2 . Had there remained less Al_2O_3 than CaO , then the former would have controlled the amount of anorthite. When this occurs, as is often the case, the residual CaO is generally combined with $(\text{Mg},\text{Fe})\text{O}$ and SiO_2 to form diopside.

The details of the above process are set forth below :—

Oxides.	Orthoclase.	Albite.	Anorthite.	Excess.
SiO_2 ...	0.0918	0.8304	0.1272	0.0006
Al_2O_3 ...	0.0153	0.1384	0.0636	0.0033
CaO ...	—	—	0.0636	None
Na_2O ...	—	0.1384	—	None
K_2O ...	0.0153	—	—	None

The excess of alumina probably implies slight alteration of the felspar, and it could be accommodated by making an algebraic calculation for muscovite (sericite) and kaolin in addition to orthoclase (see p. 405). However,

such refinement is hardly justifiable, for the analysis conforms much more closely to the theoretical composition of the felspar molecules than is usually the case.

The actual percentages of the individual felspars are arrived at in this way :—

Orthoclase

$$\begin{aligned} 0.0918\text{SiO}_2 \times 60 &= 0.0153 \times 6\text{SiO}_2 \times 60 \\ &= 0.0153\text{SiO}_2 \times 360 = 5.508 \text{ per cent.} \\ 0.0153\text{Al}_2\text{O}_3 \times 102 &= 1.561 \quad " \\ 0.0153\text{K}_2\text{O} \times 94 &= 1.438 \quad " \\ \text{Totals} \quad \underline{556} \quad \underline{8.507} \quad &" \end{aligned}$$

This may at once be simplified into

$$\begin{aligned} \text{Orthoclase} &= 0.0153 \times 556 = 8.507 \text{ per cent. Similarly,} \\ \text{Albite} &= 0.1384 \times 524 = 72.522 \quad " \quad \text{and} \\ \text{Anorthite} &= 0.0636 \times 278 = 17.681 \quad " \\ \text{Total} &= \underline{98.710} \end{aligned}$$

In the interests of accuracy this example has been worked with the molecular proportions taken to four significant figures. Working rapidly to three significant figures and using the tables, the results would come out thus :—

$$\begin{aligned} \text{Mol. prop. of Or} &= 0.015; \text{ percentage} = 8.34 \\ " \quad " \quad \text{Ab.} &= 0.138; \quad " \quad = 72.31 \\ " \quad " \quad \text{An.} &= 0.064; \quad " \quad = 17.79 \\ &\underline{98.44} \end{aligned}$$

To save further trouble the molecular proportions are often taken as whole numbers—decimal points and ciphers being avoided by the convention of multiplying the actual figures by 1,000. Thus, instead of 0.015, one can write 15. In using the tables or in calculating the conversion

to percentages, it is, of course, necessary mentally to insert the decimal point in its right place.

Garnet, South-west Finland.

As a further example, an analysis of garnet may be taken for interpretation. The mineral is from a *skarn* composed of andradite and hedenbergite, with quartz, magnetite and calcite as accessory minerals. The data are set out in the adjoining table, and a preliminary inspection of the figures shows that the sample analysed contained some hedenbergite and perhaps a little quartz.

The amount of the actual garnet molecules present is controlled by the sum of the amounts of $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$, *i.e.*, 195.

From the general formula for garnet, $3\text{RO} \cdot \text{R}_2\text{O}_3 \cdot 3\text{RO}_2$, we find, molecularly, $\text{R}_2\text{O}_3 = 195$ and $3\text{RO} = 3\text{RO}_2 = 585$.

Now the amount of RO actually present = $\text{FeO} + \text{CaO} + \text{MnO} = 615$. There is thus an excess of 30.

The amount of RO_2 actually present = $\text{SiO}_2 + \text{TiO}_2 = 625$, gives an excess of 40.

The 30 RO, distributed as 15 CaO and 15 FeO, and combined with 30 SiO_2 , gives 15 hedenbergite, $\text{CaO} \cdot \text{FeO} \cdot 2\text{SiO}_2$, leaving a final excess of 10 SiO_2 .

We may now proceed to analyse the garnet proper.

The amount of *andradite* is fixed by that of Fe_2O_3 , *i.e.*, 124.

The balance of CaO, 168, fixes the amount of *grossularite* as 56.

The amount of MnO fixes that of *spessarite* as $3\frac{1}{3}$.

The amount of Al_2O_3 now left, $11\frac{2}{3}$, gives that of *almandine*.

The constituents (except water) are now fully accounted for, and the calculation shown in the table indicates that the composition of the sample analysed may be restated as :—

Andradite	...	...	...	...	...	63.15
Grossularite	...	...	...	...	...	25.30
Spessartite	...	...	...	...	...	1.65
Almandine	...	...	...	...	...	5.82
Hedenbergite	...	...	...	...	...	3.11
Silica	...	...	...	...	...	0.60
Water	...	...	...	...	...	0.13
						<hr/>
Total	...	...	...	...	...	99.76
						<hr/>

Calculation of the Mineral Composition of Clay.

The so-called "rational" analysis of clay is an attempt to obtain by chemical means a statement of the proportions of kaolinite and other clay-minerals, feldspars, and quartz. These three groups of minerals, to which mica (mainly sericite) may, perhaps, be added, include all the essential minerals of a good clay. A rational analysis depends on the capacity of certain reagents to dissolve certain ingredients, but as the conditions controlling their action are very difficult to standardise, it is rarely that reliable results can be obtained in this way. An "ultimate" analysis of the usual kind can, however, usually be recast to yield the mineralogical information required.¹ The method of calculation fails only in the case of "bad" clays, such as those containing large quantities of carbonate minerals. For clays of the kind used in the ceramic industry no serious difficulty arises. An example will be taken from the paper by Washington referred to below.

The potash occurs in orthoclase or muscovite (sericite); soda occurs in albite or in a zeolite; lime may be present in anorthite (as plagioclase) or in a calcic zeolite; the residual alumina controls the amount of clay-substance (calculated as kaolinite); ferric oxide is probably present as limonite; and residual silica represents quartz. At the outset we must decide to rule out some of the alter-

¹ See H. S. Washington: *Journ. Amer. Ceramic Soc.*, 1, 1918, p. 405.

ANDRADITE FROM SKARN, LAKE ORIJARVI, S.W. FINLAND.

Constituents	...	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	H ₂ O	TiO ₂	MnO	Mol. Weights.		Percentages.
											Total.	Mol. Props.	
Percentages ...	...	37.13	7.27	19.74	3.60	None	31.06	0.13	0.44	0.74			
Mol. Weights ...	...	60	102	160	72	40	56	18	80	71			
Mol. Props. ...	...	619	71	124	50	—	555	7	6	10			
Hedenbergite	...	30	—	—	15	—	15	—	—	—		15 × 124.4 = 3.11	
Andradite	...	366	—	124	—	—	372	—	6	—		124 × 509.3 = 63.15	
Grossularite	...	168	56	—	—	—	168	—	—	—		56 × 451.7 = 25.30	
Spessartite	...	10	3½	—	—	—	—	—	—	10		3½ × 496.4 = 1.65	
Almandine	...	35	11½	—	35	—	—	—	—	—		11½ × 499.1 = 5.82	
Silica...	...	10	—	—	—	—	—	—	—	—		10 × 60 = 0.60	
Totals	...	519	71	124	50	—	555	—	6	10		Total ... = 99.63	

P. Eskola: *The Petrology of the Orijarvi Region*, Bull. Comm. Géol. Finlande, No. 40, 1914, p. 231.

natives. The zeolite minerals may be ignored, as they are very limited in amount, and are practically equivalent to hydrated feldspars.

<i>Constituents.</i>	<i>Percentages.</i>	<i>Mol. Props.</i>
SiO ₂	63.36	1056
Al ₂ O ₃	23.76	233
Fe ₂ O ₃	0.52	3
CaO	0.69	12
Na ₂ O	0.97	16
K ₂ O	1.63	17
H ₂ O	9.07	504
	<hr/> 100.00 <hr/>	

With orthoclase and muscovite the position is somewhat different. As shown below, it would often be possible to calculate figures for these minerals consistent with the analytical results.

Let a be the molecular amount of K₂O;

b that of H₂O after forming limonite;

and c that of Al₂O₃ after forming anorthite.

Then a , b and c are known.

Further, let x , y and z be the molecular amounts of orthoclase, muscovite, and kaolin, respectively :—

$x.$	K ₂ O.	Al ₂ O ₃ .	6SiO ₃
$y.$	K ₂ O.	2H ₂ O.	3Al ₂ O ₃ .
$z.$		2H ₂ O.	Al ₂ O ₃ .
			2SiO ₂

It is required to determine x , y and z .

From the distribution of K₂O we have

$$x + y = a.$$

From the distribution of H₂O we have

$$2y + 2z = b.$$

From the distribution of Al₂O₃ we have

$$x + 3y + z = c.$$

These three equations suffice to determine x , y and z .

The results if obtained, however, could have no serious value, as they necessarily depend on the percentage of water present. Actually the water-content of clay substance is variable, and owing to the low molecular weight of H_2O a small change in the percentage would unduly affect the results of the calculation. Considering also the possibility of error in the determination of water, and the likelihood of its presence in minerals other than those mentioned, it is clear that the calculated percentage of a mineral should not be allowed to depend on the percentage of water. For these reasons it is not advisable to attempt the calculation of muscovite, and, as a practical compromise, the requirements are sufficiently fulfilled by calculating all potash as orthoclase, and all residual alumina (after satisfying the feldspars) as kaolinite.

The mineral compounds into which the analysis may be recomputed are then as follows:—

Orthoclase, from	K_2O	$0.017 \times 556 = 9.45$
Albite, „	Na_2O	$0.016 \times 524 = 8.33$
Anorthite, „	CaO	$0.012 \times 278 = 3.34$
Kaolinite, „ residual	Al_2O_3	$0.188 \times 258 = 48.50$
Limonite, „ residual	Fe_2O_3	$0.003 \times 178 = 0.53$
Quartz, „ residual	SiO_2	$0.458 \times 60 = 27.48$
	residual H_2O	$0.125 \times 18 = 2.25$

99.88

Residual Al_2O_3 : $(233 - 17 - 16 - 12) = 0.188$

Residual SiO_2 : $(1,056 - 6 \times 17 - 6 \times 16 - 2 \times 12) = 0.458$

Residual H_2O : $(504 - 2 \times 188 - 3) = 0.125$

NOTE.—The formula for limonite is here taken as $Fe_2O_3 \cdot H_2O$ and not as $2Fe_2O_3 \cdot 3H_2O$ as usually given. See *Am. Journ. Sci.*, 1, 1919, p. 321.

If magnesia be present it suggests a chlorite, but on account of the complexity of the chlorite group Washington advocates the formation of theoretical serpentine— $3MgO \cdot 2SiO_2 \cdot 2H_2O$ (molecular weight=276) from MgO with part of the residual SiO_2 and H_2O .

If a small amount of carbon-dioxide be found it will involve no appreciable error to calculate it all as calcite,

CaCO_3 (molecular weight=100). This must be done before forming anorthite, the amount of which is then controlled by the remaining CaO .

The chief and most convenient *standard* minerals for calculating "rational" analyses of clay may thus be taken as the following:—

Quartz	...	...	\text{SiO_2	...	60
Orthoclase	..	...	$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	...	556
Albite	...	...	$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	...	524
Anorthite	...	...	$\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	...	278
Kaolinite	...	...	$2\text{H}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	...	255
Serpentine	...	...	$2\text{H}_2\text{O} \cdot 3\text{MgO} \cdot 2\text{SiO}_2$	..	276
Limonite	...	...	$\text{H}_2\text{O} \cdot \text{Fe}_2\text{O}_3$	...	178
Calcite	...	...	$\text{CaO} \cdot \text{CO}_2$	...	100

The method adopted above is manifestly conventional, but at least it may safely be claimed that it gives a closer approximation to the facts and a more reliable basis for comparison between different clays than does the "rational" analysis.

Heteromorphism in Igneous Rocks.

As we have already seen in the above discussion of comparatively simple clays, it may be quite impracticable to attempt the calculation of the actual mineral composition of a rock. In dealing with igneous rocks this difficulty becomes much more serious. The calculation of orthoclase, albite, and anorthite is easy enough, but the result does not necessarily give the percentages of the actual varieties of felspar present in the rock. Orthoclase and albite may exist together in solid solution, and calcic plagioclase may contain the constituents of orthoclase. Moreover, the constituents of plagioclase—mainly anorthite—appear to be interlocked in the complex atomic structure of some varieties of pyroxenes and amphiboles. Indeed, these two important groups of minerals are liable to be built up from so many isomorphous or partly isomorphous compounds, and they exhibit so wide a range of composition, that, with rare exceptions, it is impossible

to determine completely the actual mineral composition of an igneous rock in which they occur.

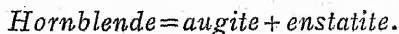
Alternative groupings of many constituents are possible, and from magmas of very similar bulk-composition very different associations of minerals may separate according to the conditions under which crystallisation takes place.

The conditions that control the formation of one mineral rather than another are mainly temperature, pressure, and the abundance and kind of volatile fluxes present in the magma. As stated in Chapter IX., volatile fluxes tend to maintain the components of a magma in solution down to much lower temperatures than could be reached in the liquid state if volatile fluxes were not present. Two sets of conditions may be conveniently contrasted :—

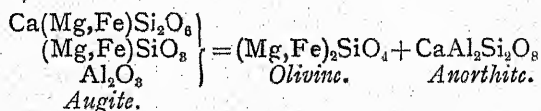
(a) Relatively low temperature and abundant volatile fluxes (implying high pressure to prevent the escape of the latter). These conditions favour the crystallisation of minerals like micas, hornblende, tourmaline and analcite.

(b) Relatively high temperature and deficiency of volatile fluxes. These conditions favour the crystallisation of minerals like olivine, pyroxenes, and leucite.

A magma consisting of the components of common hornblende could crystallise either as a hornblendite or as an enstatite-pyroxenite (websterite), as shown by the possible equation :—



Similarly, augite can be expressed as olivine and anorthite, thus :—



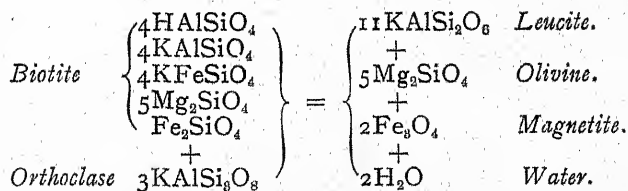
suggesting that certain pyroxenites are chemically equivalent to allivalite (olivine-anorthite rock).

From the above, we can write

Hornblende = *olivine* + *enstatite* + *anorthite*.

This equation indicates that if hornblende crystallises from a magma which also contains the components of plagioclase, the plagioclase that crystallises out is necessarily richer in the albite molecule than if olivine crystallised first. Thus the lamprophyre spessartite (hornblende and andesine) may have nearly the same composition as an olivine-dolerite or basalt (olivine, pyroxene, and labradorite). Brögger has described a still more striking case, and shows that the hornblendite of Gran (composed of a soda-bearing aluminous hornblende) has almost the same composition as a camptonite from the same vicinity (composed of less aluminous hornblende and plagioclase). Similarly the hornblendite of Garabal Hill has nearly the same chemical composition as the associated diorite of the same complex.

Fouqué and Michel-Levy, in a classic experiment, fused together microcline and biotite, and obtained from the fusion an aggregate of leucite, olivine and magnetite. The reaction may be expressed as follows :—



The association of biotite and orthoclase is a common one in granites, which have crystallised under sufficient pressure to prevent the escape of water and other fluxes. In volcanic rocks, however, biotite is comparatively rare, because water escapes from the magma, and the association of leucite with olivine is consequently found exclusively in volcanic rocks or low pressure intrusions. It is interesting to notice that some minettes (biotite-orthoclase-lamprophyre) have nearly the same composition as

some leucite-basalts (lavas composed essentially of leucite, olivine and augite).

These contrasts of mineral composition have been especially studied by Lacroix,¹ who describes the rocks exhibiting it as *heteromorphic* types. A rock to which Lacroix has given the name *mafraite* has the chemical composition of a theralite, but it contains no nepheline, as the constituents of that mineral are present in an aluminous soda-amphibole. Another rock, which he distinguishes as *fasinite*, has again the same chemical composition, but here the missing mineral is plagioclase which is hidden in a titaniferous augite. Each of these rocks is a heteromorphic type of theralite.

The Standard Minerals of the Norm.

Under these circumstances it is evidently desirable to adopt a standard series of ideal mineral-compounds as the units of expression for recomputing analyses. Such a series, made up of the simple molecules which enter into the actual but more complex minerals of igneous rocks, has been devised by the authors of the *Quantitative Classification of Igneous Rocks*, and as a result of their advocacy it has become well known and very generally adopted. Although it provides data for the classification developed by Cross, Iddings, Pirsson, and Washington, it is quite independent of that classification and is, in fact, just such a series as would naturally be drawn up by other petrologists. The list is set forth on the adjoining page, together with the formulæ in the extended form most suitable for the purpose in view, and the molecular weights corresponding to these formulæ. The standard minerals are divided into two groups as shown. One of these is called the *salic* group, the term *salic* being a mnemonic recalling silica and alumina. It includes quartz, Q; corundum, C; zircon, Z; feldspars, F; and feldspathoids, L (lenads). The other group is called *femic*, the term *femic*

¹ A. Lacroix: *C.R.*, clxv, 1917, p. 486; clxx, 1920 p. 23.

being a mnemonic calling ferromagnesian. It includes pyroxenes, P; orthosilicates (olivine and calcium orthosilicate), O; accessories containing ferrous or titanium oxides; and other accessories, A.

STANDARD MINERAL MOLECULES OF THE NORM.

Salic.

Quartz	...	...	SiO ₂	60	Q.
Corundum	...	...	Al ₂ O ₃	102	C.
Zircon	...	...	ZrO ₂ .SiO ₂	183	Z.
Orthoclase	...	...	K ₂ O .Al ₂ O ₃ .6SiO ₂	556	F.
Albite...	...	...	Na ₂ O .Al ₂ O ₃ .6SiO ₂	524	
Anorthite	...	...	CaO .Al ₂ O ₃ .2SiO ₂	278	
Leucite	...	...	K ₂ O .Al ₂ O ₃ .4SiO ₂	436	L.
Nepheline	...	...	Na ₂ O .Al ₂ O ₃ .2SiO ₂	284	
Kaliophilite	...	...	K ₂ O .Al ₂ O ₃ .2SiO ₂		
NaCl (in Sodalite)	...	...	Na ₂ .Cl ₂	117	
Na ₂ SO ₄ (in Nosean)	...	...	Na ₂ O .SO ₃	142	

Femic.

Acmite	Na ₂ O .Fe ₂ O ₃ .4SiO ₂	462	P.
Na ₂ SiO ₃ (in Pyroxene)	...	...	Na ₂ O .SiO ₂	122
Diop- { Wollastonite...	...	...	CaO .SiO ₂	116
side { Enstatite	...	...	MgO .SiO ₂	100
{ Ferrous Metasilicate	...	...	FeO .SiO ₂	132
Wollastonite	CaO .SiO ₂	116	O.
Hypers- { Enstatite	...	...	MgO .SiO ₂	100
thene { Ferrous Metasilicate	...	...	FeO .SiO ₂	132
Olivine { Forsterite	2MgO .SiO ₂	140	O.
{ Fayalite	...	...	2FeO .SiO ₂	204
Calcium Orthosilicate	...	...	2CaO .SiO ₂	172
Magnetite	FeO .Fe ₂ O ₃	232	M.
Hæmatite	...	...	Fe ₂ O ₃	160
Chromite	...	...	FeO .Cr ₂ O ₃	
Ilmenite	...	...	FeO .TiO ₂	152
Titanite (Sphene)	...	...	CaO .TiO ₂ .SiO ₂	196
Perovskite	CaO .TiO ₂ .SiO ₂	136	A.
Rutile...	...	...	TiO ₂	80
Apatite	...	...	3CaO .P ₂ O ₅ . $\frac{1}{3}$ CaF ₂	336
Fluorite	...	...	CaF ₂	78
Pyrite...	...	...	FeS ₂	
Calcite	CaO .CO ₃	100	

The composition of a rock when stated in terms of *standard* minerals is called the *norm*. The actual mineral composition stated quantitatively is distinguished as the *mode*. It must be thoroughly understood, beyond all possibility of misconception, that the norm is simply a convenient way of expressing the analysis of a rock in terms of certain ideal or *standard* mineral molecules. The latter are only units for calculation and are *not* minerals. For this reason the terms *salic* and *femic* must never be used for groups of actual minerals, but only for groups of the standard minerals of the norm. Corresponding types of actual minerals have been called *felsic* (suggesting *felspars*, *felspathoids*, and *silica*) and *mafic* (suggesting ferromagnesian minerals of all kinds). Among the micas muscovite is a felsic mineral, while biotite is mafic; and, with few exceptions, the felsic minerals are light in colour and of low specific gravity, and the mafic minerals are dark and heavy.

The Calculation of the Norm.

The list of standard minerals may seem formidable, and may suggest the prospect of a very complicated series of calculations. It must be remembered, however, that it is a general list and contains all the possibilities that may arise in thousands of analyses. In any particular case the list of mineral-molecules in terms of which the analysis is computed is likely to be quite short. Similarly, the general rules for carrying out the calculations must cover every possible case, and they are therefore more complex than those necessary for guidance with any single analysis. In practice the actual procedure varies considerably, and we shall consider a series of characteristic types which cover the vast majority of rocks. The general rules will then finally be summarised for convenience without danger of their appearing unduly complicated.

A.—The simplest cases are those in which there is an excess of silica over the amounts required to make the most

highly silicated standard minerals, *i.e.*, the alkali feldspars and hypersthene. In these quartz remains over.

Where there is a deficiency of silica three outstanding cases arise.

B.—Hypersthene may be reduced in part to olivine to meet the deficiency.

C.—If there remains a deficiency after replacing all hypersthene by olivine, then albite can be reduced in part to nepheline.

D.—If there still remains a deficiency after replacing all hypersthene by olivine, and all albite by nepheline, then orthoclase can be reduced in part to leucite.

Cases of still greater deficiency are very rare, and can be met by following the general rules.

1.—In any of the above cases there may be an excess of alumina over the amount required to make feldspars, The excess is reckoned as corundum.

2.—If, after making orthoclase (or leucite) and albite (or nepheline), the residual Al_2O_3 is less in amount than the CaO available then the residual Al_2O_3 is all used for anorthite and the residual CaO is used for diopside. Wollastonite appears only where the CaO exceeds the available $MgO + FeO$, and this rarely arises. In such a case neither hypersthene nor olivine could appear, as there would be no MgO or FeO with which to form them.

3.—If, after making orthoclase (or leucite), the residual Al_2O_3 is less in amount than the Na_2O available, then all the residual Al_2O_3 is used for albite (or nepheline), and the residual Na_2O is used for acmite.

A cross classification of the twelve types formed by combining A, B, C, and D with 1, 2, and 3 gives the groups of standard minerals listed in the adjoining page, accessory minerals being ignored.

It will be seen that the following standard minerals cannot occur together in any norm :—

Quartz with olivine, nepheline, or leucite.

Hypersthene with wollastonite, nepheline, or leucite.

Leucite with albite.
 Corundum with diopside or acmite.
 Anorthite with acmite.
 Wollastonite with hypersthene or olivine.

In the following sections actual examples are worked in detail corresponding to the five cases 1A, 3A, 2B, 2C, and 2D, these being sufficiently varied and typical to cover all the chief points that arise in making the calculations.

Before proceeding with these examples it is desirable to draw attention to the simple algebra whereby one determines the proportions of hypersthene and olivine, albite and nepheline, or orthoclase and leucite, in types B, C, and D.

B.—Let s be the residual amount of SiO_2 available for forming hypersthene and olivine, and $m+f$ the sum of the available amounts of MgO and FeO , s being less than $m+f$.

Let x be the required amount of hypersthene and y that of olivine.

Then from the formulæ

$x(\text{Mg,Fe})\text{O} \cdot \text{SiO}_2$ for hypersthene,
 and $y 2(\text{Mg,Fe})\text{O} \cdot \text{SiO}_2$ for olivine,
 we have

$$\begin{aligned} x+y &= m+f. \\ x+y/2 &= s \end{aligned}$$

whence $y = 2(m+f-s)$ = the amount of $(\text{Mg,Fe})\text{O}$ in *olivine*.

C.—Let s be the residual amount of SiO_2 available for forming albite and nepheline, and n the available amount of Na_2O , s being less than $6n$.

Let x be the required amount of albite, and y that of nepheline.

Then from the formulæ

$x(\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2)$ for albite,

THE CHIEF ASSOCIATIONS OF STANDARD MINERALS.

	$\text{Al}_2\text{O}_3 > \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO.}$	$\text{Al}_2\text{O}_3 < \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO.}$	$\text{Al}_2\text{O}_3 < \text{K}_2\text{O} + \text{Na}_2\text{O.}$
Excess of SiO_2 .	1A— Quartz Orthoclase Albite Anorthite Corundum Hypersthene	2A— Quartz Orthoclase Albite Anorthite Diopside Hypersthene	3A— Quartz Orthoclase Albite Acmite Diopside Hypersthene
Insufficient SiO_2 to complete Hypersthene.	1B— Orthoclase Albite Anorthite Corundum Hypersthene Olivine	2B— Orthoclase Albite Anorthite Diopside Hypersthene Olivine	3B— Orthoclase Albite Acmite Diopside Hypersthene Olivine
Insufficient SiO_2 to complete Albite.	1C— Orthoclase Albite Nepheline Anorthite Corundum Olivine	2C— Orthoclase Albite Nepheline Anorthite Diopside Olivine	3C— Orthoclase Albite Nepheline Acmite Diopside Olivine
Insufficient SiO_2 to complete Orthoclase.	1D— Orthoclase Leucite Nepheline Anorthite Corundum Olivine	2D— Orthoclase Leucite Nepheline Anorthite Diopside Olivine	3D— Orthoclase Leucite Nepheline Acmite Diopside Olivine

NOTE: In any of the above groups, wollastonite may appear in place of hypersthene or olivine, where there is a deficiency of $\text{MgO} + \text{FeO}$.

and $\gamma(\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.2\text{SiO}_2)$ for nepheline,
we have

$$\begin{aligned}x + y &= n \\ 6x + 2y &= s\end{aligned}$$

whence $y = \frac{6n-s}{4}$ = the amount of Na_2O in *nepheline*.

D.—Let s be the residual amount of SiO_2 available for forming orthoclase and leucite and k the amount of K_2O , s being less than $6k$.

Let x be the required amount of orthoclase, and y that of leucite.

Then from the formulæ

$x(\text{K}_2\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2)$ for orthoclase,

and $y(\text{K}_2\text{O}.\text{Al}_2\text{O}_3.4\text{SiO}_2)$ for leucite,

we have

$$\begin{aligned} x + y &= k \\ 6x + 4y &= s \end{aligned}$$

whence $y = \frac{6k-s}{2}$ = the amount of K_2O in *leucite*.

Finally, one other point must be mentioned. The group $(\text{Mg},\text{Fe})\text{O}$ appears in diopside, hypersthene, and olivine, and the question arises how the two oxides should be distributed. If only one of the three minerals appears the solution is simple: the molecular ratio $\text{MgO} : \text{FeO}$ being obviously that of the amounts available. If more than one of the three are present then the ratio of the amounts available of MgO and FeO is calculated,¹ and the two oxides are combined in that ratio throughout. In diopside there is the further limitation that $\text{CaO} : \text{MgO} + \text{FeO} = 1 : 1$.

Granite, Dartmoor (Type 1A).

The details of the analysis and the computation into standard minerals are set out on page 415.

(a) Determine the molecular proportions of each of the oxides recorded in the analysis.

¹ In practice it is better to calculate the ratio $\text{FeO} : \text{MgO} + \text{FeO}$, since in each of the three minerals the sum of the two oxides is what is known.

(b) Determine the accessory mineral molecules—

(1) $\text{TiO}_2 : \text{FeO} = 3 : 3 \dots$... for *Ilmenite*.

(2) $\text{P}_2\text{O}_5 : \text{CaO} = 1 : 4 \dots$... for *Apatite*.

The proportion here should be as 3 : 10, and working to three significant figures 1 : 4 is more accurate than 1 : 3, since the "1" is really 0.0013.

(3) Inspection shows that $\text{Al}_2\text{O}_3 > \text{Na}_2\text{O} + \text{K}_2\text{O} +$ residual CaO , (132 > 98) and consequently no Fe_2O_3 is required for acmite. All the Fe_2O_3 is therefore used for magnetite.

$\text{Fe}_2\text{O}_3 : \text{FeO} = 5 : 5 \dots$ for *Magnetite*.

(c) $\text{K}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 40 : 40 : 6 \times 40$ for *Orthoclase*.

(d) $\text{Na}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 50 : 50 : 6 \times 50$ for *Albite*.

(e) $\text{CaO} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 8 : 8 : 2 \times 8$ for *Anorthite*.

The CaO used here is that remaining after operation (b2).

(f) Residual $\text{Al}_2\text{O}_3 = 34 \dots$... for *Corundum*.

(g) $\text{MgO} = 19$ and residual $\text{FeO} = 7$, $\text{MnO} = 2$ is added to FeO . These are used for hypersthene.

$\text{MgO} : \text{SiO}_2 = 19 : 19 \dots$ for *Hypersthene*.
 $\text{FeO} + \text{MnO} : \text{SiO}_2 = 9 : 9 \dots$

(h) Residual $\text{SiO}_2 = 668 \dots$... for *Quartz*.

The molecular proportions of each standard mineral, the molecular weights, and finally the percentages, are given on the right of the Table on page 419.

Ægirine-riebeckite-granite, Angola (Type 3A).

(a) Inspection of the molecular proportions shows that Al_2O_3 is less in amount than $\text{K}_2\text{O} + \text{Na}_2\text{O}$. After making orthoclase, and albite as far as the Al_2O_3 allows, the residual Na_2O is calculated as acmite and the residual Fe_2O_3 then determines magnetite. The determination of magnetite must therefore be postponed until after the formation of acmite.

(b) Determine the accessory mineral molecules—

(1) $\text{ZrO}_2 : \text{SiO}_2 = 4 : 4 \dots$... for *Zircon*.

(2) $\text{TiO}_2 : \text{FeO} = 4 : 4 \dots$... for *Ilmenite*.

(c) $\text{K}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 47 : 47 : 6 \times 47$ for *Orthoclase*.

(d) Residual $\text{Al}_2\text{O}_3 = 40$, and determines albite.

$\text{Na}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 40 : 40 : 6 \times 40$ for *Albite*.

(e) Residual $\text{Na}_2\text{O} = 20$, and determines acmite.

$\text{Na}_2\text{O} : \text{Fe}_2\text{O}_3 : \text{SiO}_2 = 20 : 20 : 4 \times 20$ for *Acmite*.

(f) Residual $\text{Fe}_2\text{O}_3 = 1$ and determines magnetite.

$\text{Fe}_2\text{O}_3 : \text{FeO} = 1 : 1 \dots$... for *Magnetite*.

(g) $\text{CaO} : \text{MgO} + \text{FeO} : \text{SiO}_2 = 10 : 10 : 20$ for *Diopside*.

The ratio of MgO to FeO at this stage is 2 : 44, and the nearest possible ratio in diopside is therefore 1 : 9, leaving 1 : 35 for hypersthene.

(h) $\text{MgO} + \text{FeO} : \text{SiO}_2 = 1 + 35 : 36 \dots$ for *Hypersthene*

The hypersthene here is practically FeO. SiO_2 corresponding to the presence of riebeckite in the rock.

The actual mineral composition of the rock is—

Major Constituents.			Minor Constituents.	
Quartz	...	32	(n.d.)	
Alkali-felspars	...	48	Zircon.	
Riebeckite...	...	16	Ilmenite.	
Ægirine	...	4	Limonite.	
		<hr/>	Sericite or kaolin.	
		100		

Olivine-basalt, Iceland (Type 2B).

(a) Inspection of the molecular proportions shows that Al_2O_3 is greater in amount than $\text{Na}_2\text{O} + \text{K}_2\text{O}$, but less than $\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}$. Consequently no corundum will appear, and, after making anorthite, CaO will be left over for diopside. All the Fe_2O_3 is available for magnetite.

(b) Determine the accessory mineral molecules—

(1) $\text{TiO}_2 : \text{FeO} = 30 : 30 \dots$... for *Ilmenite*.

(2) $\text{P}_2\text{O}_5 : \text{CaO} = 1 : 3 \dots$... for *Apatite*.

GRANITE, HAY TOR, DARTMOOR.

ANALYSES: INTERPRETATION

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Constituents ...	Percentages.													Mol. Weights.	Total.	
	100.131															
Percentages ...	Mol. Profs.													Mol. Profs.	Total.	
Mol. Weights	Mol. Profs.															
Mol. Profs. ...	Mol. Profs.															
SiO ₂	75.09	13.46	0.74	1.05	0.74	0.66	3.10	3.78	0.91	0.25	0.19	0.14	—	—	60	.668
Al ₂ O ₃	60	102	160	72	40	56	62	94	18	80	142	71	—	—	556	.040
Fe ₂ O ₃	1252	132	5	15	19	12	50	40	—	3	1+	2	—	—	524	.050
FeO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	278	.008
MgO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	102	.034
CaO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	132	.009
Na ₂ O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	100	.019
K ₂ O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	232	.005
H ₂ O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	152	.003
TiO ₂	—	—	—	—	—	—	—	—	—	—	—	—	—	—	336	.001+
P ₂ O ₅	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
MnO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Quartz	668	—	—	—	—	—	—	—	—	—	—	—	—	—	60	.668
Orthoclase	240	40	—	—	—	—	—	40	—	—	—	—	—	—	556	.040
Albite	300	50	—	—	—	—	50	—	—	—	—	—	—	—	524	.050
Anorthite	16	8	—	—	—	8	—	—	—	—	—	—	—	—	278	.008
Corundum	—	34	—	—	—	—	—	—	—	—	—	—	—	—	102	.034
Hypersthene	9	—	—	7	—	—	—	—	—	—	—	2	—	—	132	.009
Magnetite	19	—	—	—	19	—	—	—	—	—	—	—	—	—	100	.019
Ilmenite	—	—	5	5	—	—	—	—	—	—	—	—	—	—	232	.005
Apatite	—	—	—	3	—	—	—	—	—	—	—	—	—	—	152	.003
	—	—	—	—	—	4	—	—	—	—	—	—	—	—	336	.001+

Includes 0.02 per cent. of CO₂.

$$\begin{aligned} \text{H}_2\text{O} + \text{CO}_2 &= \frac{99.17}{0.93} \\ \text{Total} &= \frac{100.10}{1} \end{aligned}$$

Mem. Geol. Surv., 338, 1912, p. 42. Analyst, E. G. Radley.

ÆGIRINE-RIBBECKITE-GRANITE, LOWER CONGO, ANGOLA.

Constituents ...	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	TiO ₂	ZrO ₂	Total.	Mol. Weights.	Percentages.
												100/65		
Percentages ...	74.66	8.85	3.26	3.54	0.09	0.53	3.68	4.46	0.75	0.32	0.51			
Mol. Weights	60	102	160	72	40	56	62	94	18	80	123			
Mol. Profs. ...	1244	87	21	49	2	10	60	47	—	4	4			
Quartz...	582	—	—	—	—	—	—	—	—	—	—	.582	60	34.92
Orthoclase ...	282	47	—	—	—	—	—	47	—	—	—	.047	556	26.13
Albite ...	240	40	—	—	—	—	40	—	—	—	—	.040	524	20.26
Zircon ...	4	—	—	—	—	—	—	—	—	—	4	.004	183	0.73
Acmite...	80	—	20	—	—	—	20	—	—	—	—	.020	462	9.24
Diopside	10	—	—	—	—	10	—	—	—	—	—	.010	116	1.16
	1	—	—	—	1	—	—	—	—	—	—	.001	100	0.10
	9	—	—	9	—	—	—	—	—	—	—	.009	132	1.20
Hypersthene	1	—	—	—	1	—	—	—	—	—	—	.001	100	0.10
	35	—	—	35	—	—	—	—	—	—	—	.035	132	4.62
Magnetite ...	—	—	1	1	—	—	—	—	—	—	—	.001	232	0.23
Ilmenite	—	—	—	4	—	—	—	—	—	4	—	.004	152	0.61

A. Holmes: *Geol. Mag.*, 1915, p. 267. Analyst, A. Holmes.

100.00
Water = .75

Total = 100.75

OLIVINE-BASALT, ICELAND.

ANALYSES: INTERPRETATION

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Constituents ...	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	TiO ₂	P ₂ O ₅	MnO	Total. 100.12 ¹	Mol. Weights.	Percentages.
Percentages ...	47.27	14.44	0.97	10.15	10.30	11.73	1.86	0.18	0.42	2.36	0.12	0.19			
Mol. Weights...	60	102	160	72	40	56	62	94	18	80	142	71			
Mol. Props. ...	788	142	6	142	257	209	30	2	—	30	1	3			
Orthoclase	12	2	—	—	—	—	—	2	—	—	—	—	.002	556	1.11
Albite ...	180	30	—	—	—	—	30	—	—	—	—	—	.030	524	15.72
Anorthite	220	110	—	—	—	110	—	—	—	—	—	—	.110	278	30.58
Diopside	96	—	—	—	—	96	—	—	—	—	—	—	.096	116	11.14
	68	—	—	—	68	—	—	—	—	—	—	—	.068	100	6.80
Hypersthene	28	—	—	28	—	—	—	—	—	—	—	—	.028	132	3.70
	69	—	—	—	69	—	—	—	—	—	—	—	.069	100	6.90
Olivine...	29	—	—	29	—	—	—	—	—	—	—	—	.029	132	3.83
	60	—	—	—	120	—	—	—	—	—	—	—	.060	140	8.40
Magnetite	26	—	—	52	—	—	—	—	—	—	—	—	.026	204	5.30
	...	—	6	6	—	—	—	—	—	—	—	—	.006	232	1.39
Ilmenite	...	—	—	30	—	—	—	—	—	—	—	—	.030	152	4.56
Apatite...	...	—	—	—	—	3	—	—	—	30	—	—	.001	336	0.34

¹ Includes Cl = 0.01; Cr₂O₃ = 0.04; V₂O₅ = 0.07; NiO = 0.01.

A. Holmes: *Min. Mag.*, xviii., 1918, p. 196. Analyst, H. F. Harwood.

Water, etc. = 99.77
0.55

Total = 100.32

PETROGRAPHIC METHODS

A small percentage of Cl is recorded, and is probably present in apatite, but the amount is too small to consider in the calculation.

(3) $\text{Fe}_2\text{O}_3 : \text{FeO} = 6 : 6$... for *Magnetite*.

The amounts of Cr_2O_3 , V_2O_5 , and NiO are so small that they may be neglected.

(c) $\text{K}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 2 : 2 : 6 \times 2$... for *Orthoclase*.

(d) $\text{Na}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 30 : 30 : 6 \times 30$ for *Albite*.

(e) Residual $\text{Al}_2\text{O}_3 = 110$, and determines anorthite.

$\text{CaO} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 110 : 110 : 220$ for *Anorthite*.

(f) Residual $\text{CaO} = 96$, and determines diopside.

$\text{CaO} : \text{MgO} + \text{FeO} : \text{SiO}_2 = 96 : 96 : 192$ for *Diopside*.

The ratio of MgO to FeO at this stage is $257 : 106$. MnO may be added to FeO , giving a ratio $257 : 109$. The actual amounts of MgO and FeO for diopside must be as nearly as possible in this ratio and in sum amounting to 96. Now

the ratio $\frac{\text{FeO}}{\text{MgO} + \text{FeO}} = \frac{109}{366} = 0.29$. The amount of FeO in diopside is therefore $96 \times 0.29 = 28$, giving that of MgO as 68.

(g) The residual $\text{MgO} + \text{FeO}$ now amounts to 270, whereas the residual silica still available is only 184. Consequently it is impossible to use all the $\text{MgO} + \text{FeO}$ for hypersthene.

Hence, $y = 2(270 - 184) = 172$ = the amount of $\text{MgO} + \text{FeO}$ in olivine; and $x = 270 - 172 = 98$ = the amount of $\text{MgO} + \text{FeO}$ in hypersthene.

$\text{MgO} + \text{FeO} : \text{SiO}_2 = 98 : 98$... for *Hypersthene*.

The amount of $\text{FeO} = 98 \times 0.29 = 29$, giving that of MgO as 69.

(h) $\text{MgO} + \text{FeO} : \text{SiO}_2 = 172 : 86$... for *Olivine*.

The amount of $\text{FeO} = 172 \times 0.29 = 50$, giving that of MgO as 122.

The actual mineral composition of the rock is—

			By Volume.		By Weight.
Bytownite	...	...	48	...	43
Pyroxene	...	...	37	...	37
Olivine	...	...	11	...	12
Magnetite and Ilmenite	...	...	4	...	8
			100		100

Phonolite, Wolf Rock, Cornwall (Type 2C).

(a) Inspection of the molecular proportions shows that, as in the last two cases, no corundum can be present, and that, after forming anorthite, some CaO remains.

(b) Determine the accessory mineral molecules—

(1) $\text{Fe}_2\text{O}_3 : \text{FeO} = 14 : 14$... for *Magnetite*.

(2) Residual $\text{Fe}_2\text{O}_3 = 3$... for *Hematite*.

(c) $\text{K}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 30 : 30 : 6 \times 30$ for *Orthoclase*.

(d) $\text{Na}_2\text{O} : \text{Al}_2\text{O}_3 = 179 : 179$ for albite and nepheline.

It is clearly impossible to use the whole of the Na_2O for albite, as that would require SiO_2 amounting to 1074, more than the rock contains. The proportions of albite and nepheline cannot be determined until after (f), when the available SiO_2 can be calculated.

(e) Residual $\text{Al}_2\text{O}_3 = 9$ and determines anorthite.

$\text{CaO} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 9 : 9 : 2 \times 9$... for *Anorthite*.

(f) Residual $\text{CaO} = 16$.

There is no MgO or FeO with which to combine the CaO , and the latter must therefore be calculated as wollastonite. For the same reason there is no olivine.

$\text{CaO} : \text{SiO}_2 = 16 : 16$... for *Wollastonite*

(g) We now return to (d), in which SiO_2 has not yet been allotted.

The residual SiO_2 is found to be 727, and this may be distributed between x albite and y nepheline

$$x + y = 179$$

$$6x + 2y = 727$$

$$2x + 2y = 358$$

$$4x = 369$$

whence, $x = 92$, and $y = 87$.

NOSEAN-PHONOLITE, WOLF ROCK, NEAR LAND'S END.

Constituents ...	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	P ₂ O ₅	MnO	Total. 99.60	Mol. Weights.	Percentages.
Percentages ...	56.43	22.25	2.66	0.97	tr.	1.35	11.12	2.77	2.05	tr.	tr.	99.60		
Mol. Weights...	60	102	160	72	40	56	62	94	18	142	71			
Mol. Props. ...	941	218	17	14	—	25	179	30	—	—	—			
Orthoclase ...	180	30	—	—	—	—	—	30	—	—	—	.030	556	16.68
Albite ...	552	92	—	—	—	—	92	—	—	—	—	.092	524	48.21
Nepheline ...	174	87	—	—	—	—	87	—	—	—	—	.087	284	24.71
Anorthite ...	18	9	—	—	—	9	—	—	—	—	—	.009	278	2.50
Wollastonite ...	16	—	—	—	—	16	—	—	—	—	—	.016	116	1.86
Magnetite ...	—	—	14	14	—	—	—	—	—	—	—	.014	232	3.25
Hæmatite ...	—	—	3	—	—	—	—	—	—	—	—	.003	160	0.48

See J. J. H. Teall: *British Petrography*, 1888, p. 388. Analyst, Phillips.97.69
Water = 2.05

Total = 99.74

$\text{Na}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 92 : 92 : 6 \times 92$ for *Albite*.

$\text{Na}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 87 : 87 : 2 \times 87$ for *Nepheline*.

Leucite-tephrite, Vesuvius (Type 2D).

(a) As before, inspection shows that there can be no corundum or acmite, and that diopside can be formed after anorthite.

(b) Determine the accessory mineral molecules—

(1) $\text{TiO}_2 : \text{FeO} = 13 : 13$... for *Ilmenite*.

(2) $\text{Fe}_2\text{O}_3 : \text{FeO} = 9 : 9$... for *Magnetite*.

(c) $\text{K}_2\text{O} : \text{Al}_2\text{O}_3 = 75 : 75$ for orthoclase and leucite.

Even after making olivine instead of hypersthene, and nepheline instead of albite, it will be found that insufficient SiO_2 remains to calculate all the K_2O as orthoclase. The proportions of orthoclase and leucite cannot yet be determined.

(a) $\text{Na}_2\text{O} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 44 : 44 : 2 \times 44$ for *Nepheline*.

(e) Residual $\text{Al}_2\text{O}_3 = 63$ and determines anorthite.

$\text{CaO} : \text{Al}_2\text{O}_3 : \text{SiO}_2 = 63 : 63 : 2 \times 63$ for *Anorthite*.

(f) Residual $\text{CaO} = 101$ and determines diopside.

$\text{CaO} : \text{MgO} + \text{FeO} : \text{SiO}_2 = 101 : 101 : 2 \times 101$

for *Diopside*.

The ratio of $\text{MgO} : \text{Fe}$ is easily found to be

54 : 47.

(g) Residual $\text{MgO} + \text{FeO} = 79$ and determines olivine

since there is insufficient SiO_2 for hypersthene.

$\text{MgO} + \text{FeO} : \text{SiO}_2 = 79 : 79/2$... for *Olivine*.

The ratio of $\text{MgO} : \text{FeO} = 42 : 37$.

(h) We may now return to (c), in which no SiO_2 has yet been allotted.

The residual SiO_2 is found to be 336, and this may be distributed between x orthoclase and y leucite.

$$x + y = 75$$

$$6x + 4y = 336$$

$$4x + 4y = 300$$

$$2x = 36$$

whence, $x = 18$, and $y = 57$

LEUCITE-TEPHRITE, LAVA OF 1906, VESUVIUS.

Constituents ...	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O	TiO ₂	P ₂ O ₅	Total. 100.32	Mol. Props.	Mol. Weights.	Percentages.
Percentages ...	48.28	18.39	1.12	7.88	3.72	9.20	2.84	7.25	0.62	1.28	0.51				
Mol. Weights...	60	102	160	72	40	56	62	94	18	80	142				
Mol. Props. ...	792	182	9	106	96	164	44	75	—	13	—				
Orthoclase ...	108	18	—	—	—	—	—	18	—	—	—	.018	556	10.01	
Leucite ...	228	57	—	—	—	—	—	57	—	—	—	.057	436	24.85	
Nepheline ...	88	44	—	—	—	—	44	—	—	—	—	.044	284	12.50	
Anorthite ...	126	63	—	—	—	63	—	—	—	—	—	.063	278	17.51	
Diopside	101	—	—	—	—	101	—	—	—	—	—	.101	116	11.72	
	54	—	—	—	54	—	—	—	—	—	—	.054	100	5.40	
Olivine	47	—	—	47	—	—	—	—	—	—	—	.047	132	6.20	
	21	—	—	—	42	—	—	—	—	—	—	.021	140	2.94	
Magnetite	19	—	—	37	—	—	—	—	—	—	—	.019	204	3.88	
	—	—	9	9	—	—	—	—	—	—	—	.009	232	2.09	
Ilmenite	—	—	—	13	—	—	—	—	—	13	—	.013	152	1.98	

A. Lacroix: C. R., cxliii, 1906, p. 14.

$$\text{P}_2\text{O}_5 + \text{Water} = 99.08$$

$$\text{Total} = 100.21$$

$K_2O : Al_2O_3 : SiO_2 = 18 : 18 : 6 \times 18$ for *Orthoclase*.

$K_2O : Al_2O_3 : SiO_2 = 57 : 57 : 4 \times 57$ for *Leucite*.

General Rules for Calculating the Norm.

The particular methods of calculation hitherto adopted will now be generalised into a systematic scheme designed to meet every possibility that is likely to arise in igneous rocks.

With the exception of magnetite and haematite the accessory standard minerals are first arranged for. The silicate minerals are then taken in order, but silica is not allotted until the distribution of the other constituents among themselves has been decided. Certain associations, such as anorthite and diopside, are inflexible, and must first be satisfied with silica. Other associations, such as hypersthene and olivine, or albite and nepheline, offer alternatives, and at the outset they are given the minimum amount of silica, and later, if it be possible, that amount is raised.

A.—Determine the molecular proportions (or amount) of each constituent of the rock as recorded in the analysis.

B.—Add the amount of—

(a) MnO and NiO to that of FeO.

(b) BaO and SrO to that of CaO.

C.—Make allotments of molecular amounts in the order and ratios stated below:—

(a) Independent Accessory Mineral Molecules.

1. $Cr_2O_3 : FeO = 1 : 1$... for *Chromite*.

2. $TiO_2 : FeO = 1 : 1$... for *Ilmenite*.

Residual $TiO_2 : CaO = 1 : 1$... for *Perovskite*.

This may later be raised to titanite if silica be available. See p. 431.

Residual TiO_2 (if any) ... for *Rutile*.

3. $P_2O_5 : CaO = 3 : 10$ }
 $P_2O_5 : F = 3 : 1$ } ... for *Apatite*.

Where F is not recorded the second part of this allotment must be ignored.

4. Residual $F : CaO = 2 : 1$... for *Fluorite*.
5. $Cl : Na_2O = 2 : 1$... for *NaCl* (in *sodalite*).
6. $SO_3 : Na_2O = 1 : 1$... for *Na_2SO_4* (in *nosean*).

If the rock contains no minerals of the nosean-haüyne group, SO_3 probably represents S and should be allotted to pyrite.

7. $S : FeO = 2 : 1$... for *Pyrite*.
8. If the rock contains *cancrinite*—
 $CO_3 : Na_2O = 1 : 1$... for *Na_2CO_3*
 If the rock contains *calcite*—
 $CO_3 : CaO = 1 : 1$... for *Calcite*.
9. $ZrO_2 = SiO_2 = 1 : 1$... for *Zircon*.

Magnetite and hæmatite can be dealt with later only when acmite is present.

(b) *Allotment of Bases and Dependent Accessories.*

10. $K_2O : Al_2O_3 = 1 : 1$ for *Orthoclase*, *Leucite*, or *Kaliophilite*.

If there should be an excess of K_2O over Al_2O_3 (extremely rare), it is reckoned as $K_2O.SiO_2$.

11. $Na_2O : Al_2O_3 = 1 : 1$... for *Albite* or *Nepheline*.
 Residual $Na_2O : Fe_2O_3 = 1 : 1$.. for *Acmite*.
 Residual Na_2O (rare) is reckoned as $Na_2O.SiO_2$.
12. Residual $Fe_2O_3 : FeO = 1 : 1$... for *Magnetite*.
 Residual Fe_2O_3 ... for *Hæmatite*.
13. Residual $Al_2O_3 : CaO = 1 : 1$... for *Anorthite*.
 Residual Al_2O_3 ... for *Corundum*.
14. Residual $CaO : MgO + FeO = 1 : 1$ for *Diopside*.

At this stage the ratio of MgO and still available FeO is determined, and this ratio is preserved to the nearest significant figure in *diopside*, *hypersthene*, and *olivine*.

- Residual CaO ... for *Wollastonite* or $2CaO.SiO_2$
15. Residual $MgO + FeO$ for *Hypersthene* or *Olivine*.

All the oxides have now been distributed except SiO_2 and to this we now turn.

(c) Allotment of Silica.

NOTE :— SiO_2 has already been allotted to ZrO_2 , SiO_2 , zircon, $\text{Na}_2\text{O} \cdot \text{SiO}_2$ and $\text{K}_2\text{O} \cdot \text{SiO}_2$.

16. $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$... for *Anorthite*.
17. $\text{CaO} \cdot (\text{MgO} + \text{FeO}) \cdot 2\text{SiO}_2$... for *Diopside*.
18. $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 4\text{SiO}_2$... for *Acmite*.
19. $2(\text{MgO} + \text{FeO}) \cdot \text{SiO}_2$ (see 24) ... for *Olivine*.
20. $\text{CaO} \cdot \text{SiO}_2$ (see 22, Note B) ... for *Wollastonite*.
21. $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ (see 23, Note) for *Nepheline*.
22. $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$... for *Orthoclase*.

NOTE A :—If the available SiO_2 at this stage be insufficient to make orthoclase, then distribute between orthoclase (x molecules) and leucite (y molecules)—

$$x + y = \text{the available amount of } \text{K}_2\text{O}.$$

$$6x + 4y = \text{the available amount of } \text{SiO}_2.$$

NOTE B :—If there is insufficient silica to form leucite (a very rare case) then wollastonite (see 20) must be reduced to $2\text{CaO} \cdot \text{SiO}_2$, and if this still fails to give the required amount, or if there is no wollastonite, then diopside (see 17) must be reduced wholly or in part to $2\text{CaO} \cdot \text{SiO}_2$ and olivine. If this still fails to complete the formation of leucite, then the available SiO_2 is distributed between leucite and kaliophilite. These complications so rarely arise that for all practical purposes they may be ignored. See H. S. Washington: *Journ. Wash. Acad. Sci.*, v, 1915, p. 345; and *Chemical Analyses of Igneous Rocks*, U.S.G.S. Prof. Pap. 99, 1917, p. 1165.

23. If residual SiO_2 remains after 22, convert nepheline into $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$... for *Albite*.

NOTE :—If the available SiO_2 at this stage be insufficient to make albite, then distribute between albite (x molecules) and nepheline (y molecules)—

$$x + y = \text{the available amount of } \text{Na}_2\text{O}.$$

$$6x + 2y = \text{the available amount of } \text{SiO}_2.$$

24. If residual SiO_2 remains after 23, convert olivine into $(\text{MgO} + \text{FeO}) \cdot \text{SiO}_2$... for *Hypersthene*.

[illegible]

Fig. 59.—Form (reduced) for the calculation of the norm.

NOTE :—If the available SiO_2 at this stage be insufficient to make hypersthene, then distribute between hypersthene (x molecules) and olivine (y molecules)—

$x+y$ = the available amount of $\text{MgO} + \text{FeO}$.

$x+y/2$ = the available amount of SiO_2 .

25. If residual SiO_2 remains after 24, convert perovskite (if any) into $\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$ for *Titanite*.

26. Residual SiO_2 finally remaining is reckoned as

Quartz.

D.—Determine the percentage weights of the standard minerals actually occurring in the norm under consideration. The molecular proportions, units of calculation, and percentages are set forth in the tables of Appendix B.

Form for setting out the Calculation.

The five calculations already made to illustrate the procedure in typical examples are set out according to a systematic scheme which enables the necessary work to be done rapidly and neatly. A good deal of unnecessary work, however, is involved in writing out the constituents and the names of the standard minerals. A general form has therefore been drawn up to meet the requirements of the vast majority of cases that arise, and this is reproduced on the adjoining page. The constituents, as stated in analyses, are listed horizontally, this being far more convenient than the usual vertical arrangement. Beneath each constituent a space is left for the percentage, and below this the molecular weight is given, the two constituting in each case a division sum which gives the molecular proportion, to be written in the space below. Vertically, on the left, is a list of the chief standard minerals with their extended formulæ. After corundum a blank is left for any additional silic minerals, such as zircon, which may occasionally be required, and, after calcite, a blank for additional femic minerals, such as perovskite or titanite. The various allotments of molecular amounts are made in the divisions obtained by

crossing constituents against standard minerals. On the right the ascertained molecular amounts of each standard mineral are to be written, and each of these multiplied by the appropriate molecular weight (placed in the next column), gives the required percentage. For the convenience of those using the C.I.P.W. Quantitative Classification, the criteria for deciding the position of the rock (for Classes I, II and III) are placed at the bottom of the form.

The form may thus be used for determining the formulæ of many silicate minerals from their analyses; for calculating the standard mineral analyses of clays; for calculating the norms of igneous rocks; and, if desirable, for ascertaining the position of an analysis in the C.I.P.W. Quantitative Classification. Separate copies of the form (foolscap size) may be obtained from the publishers of this book.

The Relation of the Norm (Calculated) to the Mode (Actual).

In calculating the norm preference is given in all cases to the higher silicates whenever this is possible. Thus alkali-felspars have priority over feldspathoids, and hypersthene has priority over olivine. In the actual minerals of the rock this artificial preference is not necessarily carried to the same degree of completeness. Potash may be present as an orthosilicate in micas, and soda may occur as metasilicate in amphiboles and pyroxenes. Moreover, titanium dioxide may take the place of silica in certain minerals. For these reasons, if the rock contains free silica, *i.e.*, if it be *oversaturated*, the norm will in general show less quartz than the mode; and felspars and feldspathoids together will always be more abundant in the norm than in the mode. The Shap granite, for which the mode has been accurately determined, may be taken as an example illustrating these relations:—

<i>Minerals.</i>	<i>Mode.</i>	<i>Norm.</i>
Quartz	24.4	21.9
Felspars	69.8	71.0
Biotite	5.8	—
Other norm-minerals ¹ ...	—	6.3

In alkali-rocks it may happen that iron oxides calculated as magnetite in the norm are represented in part by ferrous silicate in the mode, that compound being present in many soda-amphiboles. In such a case the norm might contain slightly more quartz than the mode, though the likelihood of its arising is remote. The ægirine-riebeckite granite of Angola (p. 417) provides an example of this kind, but the amount of magnetite in the norm is so small that it would not appreciably affect the silica relations. One would, however, expect a close agreement between mode and norm, at least as far as groups of minerals are concerned. The figures are :—

<i>Minerals.</i>	<i>Mode.</i>	<i>Norm.</i>
Quartz	32	34.9
Alkali-felspars	48	47.8
Soda-pyroxenes, amphiboles and accessories	20	18.0

The discrepancies are not great, but they are in the wrong direction, and the reason for this probably lies in the fact that the mode was measured by the micrometric method on sections giving not quite typical proportions. This is not a gratuitous assumption, for the rock is not of homogeneous texture, and the sections were cut obliquely to a slight primary foliation. Consequently the proportion of dark minerals would be greater in the sections than in the rock itself; quartz would be slightly deficient, and felspars, having a less elongated habit than the dark minerals and a less granular habit than the quartz would presumably not be very different from the correct value. These deductions are supported by the norm.

¹ Includes 0.6 per cent. of corundum.

The presence of corundum in a norm may mean that of corundum in the mode, but more generally it corresponds with the presence of mica (as in Shap granite), or with sericitisation or kaolinisation of the feldspars. Andalusite, topaz, and other aluminous minerals other than feldspars and feldspathoids would similarly lead to the appearance of corundum in the norm.

Among feldspathoidal rocks the association of orthoclase and nepheline is common, whereas that of albite and leucite is rare. This fact is applied in calculating the norm, for in the latter albite and leucite cannot appear together. In actual rocks, however, we find leucite commonly associated with calcic plagioclase, the reason being that the presence of abundant anorthite predisposes the crystallisation with it of albite (isomorphous) rather than nepheline (not isomorphous).¹ In such rocks there will necessarily be a marked lack of correspondence, qualitatively as well as quantitatively, between norm and mode.

Except by a rare coincidence the norm must contain either quartz or one of the minerals olivine, nepheline and leucite. Thus, if a classification of igneous rocks were to be based on the silica-saturation principle,² using norm-minerals instead of those actually developed, it would not be possible to have a saturated class from which quartz, olivine and feldspathoids were alike excluded. Yet, when the actual minerals are considered, it is not only convenient but quite possible to form such a class. The reason lies partly in the fact that normative minerals may be combined as solid solutions in the actual mode-minerals, and partly because in certain rocks it may be quite impossible to detect small quantities of quartz, nepheline, etc., even though they may presumably be present. Minerals—or potential minerals—that are hidden by their isomorphism with others have been called *occult* by

¹ J. P. Iddings: *Igneous Rocks*, I, 1909, pp. 134-6.

² S. J. Shand: *Geol. Mag.*, 1913, p. 508; 1914, p. 485; 1915, p. 339.

A. Holmes: *Geol. Mag.*, 1917, p. 115.

The Nomenclature of Petrology, 1920, App. E.

Iddings. The heteromorphic rocks of Lacroix are thus those which contain certain critical minerals in the "occult" state. It thus becomes practicable to recognise a class of saturated rocks which shall include most of those lying near the theoretical boundary between oversaturated and undersaturated types. The saturated rocks have, in fact, an apparently simple mineral composition which, tested by the norm, is found to be more complex; and if the norm were used as a strict criterion of the degree of saturation, the possibility of an exactly saturated rock would be infinitely small.

Chemical Criteria of the Parentage of Metamorphic Rocks.

One of the fundamental problems that arises in the study of metamorphic rocks is the determination of their antecedents, whether igneous or sedimentary. In many cases field-observations yield unequivocal evidence, and mineral composition and structure may both provide important clues which often are quite conclusive. When these fail to disclose the parentage satisfactorily, there remains for consideration the chemical composition, if available.

As a preliminary to the discussion of the nature and validity of the chemical criteria it is necessary to contrast the outstanding characters of igneous and sedimentary rocks from a chemical standpoint. The processes of denudation and deposition lead mechanically to the separation of arenaceous and argillaceous types of sediment, and chemically to the removal in solution of sodium in greater amount than potassium, and of calcium in greater amount than magnesium. The sodium remains for the most part in solution, while the calcium enters largely into limestones and detrital sediments as carbonate. In general there is little difficulty in recognising the parentage of metamorphic rocks derived from calcareous and arenaceous rocks, and we may therefore con-

fine our attention to a comparison between argillaceous and igneous rocks.

Clearly the former should be, on an average, poorer in alkalies and lime than the latter. For this reason argillaceous rocks should show an excess of alumina over the amount required to satisfy the felspathic bases, and this excess should, in general, be greater than is likely to be met with in igneous rocks. Actual figures collected by Bastin,¹ who has discussed the whole problem in detail, show that this is the case. Over 60 per cent. of schists and gneisses of argillaceous origin contain a calculated excess of alumina (corundum in the norm) greater than five per cent., and in half of these the excess is greater than ten per cent. The corresponding proportions for igneous rocks are less than three per cent. and 0.6 per cent. respectively.

In igneous rocks there is, on an average, more soda than potash, but, as a result of weathering and the selective removal of soda, sediments contain, on an average, more potash than soda. Taking actual rocks, Bastin found that 92 per cent. of shales and slates, and 83 per cent. of metamorphic rocks derived from argillaceous sediments, contain more potash than soda. The corresponding figure for igneous rocks was about 50 per cent. This criterion is evidently not very satisfactory, especially when one considers the great abundance of granites, syenites and other igneous rocks of analogous composition in which orthoclase and biotite may be abundant.

The difficulty may be overcome, however, by combining the alkali criterion with one based on the percentages of lime and magnesia. Igneous rocks, on an average, contain more lime than magnesia; while in sediments, again because of selective solution, magnesia becomes more abundant than lime. (Limestones are, of course, here left out of account.) Actual figures show that 84 per

¹ E. S. Bastin: *Journ. Geol.*, xvii, 1909, p. 449.

cent. of argillaceous rocks, and 77 per cent. of metamorphic rocks derived from them, contain more magnesia than lime. For igneous rocks the figure is only 43 per cent. Here again the criterion taken alone is unsatisfactory, the reason being that there are many igneous rocks in which olivine and other ferromagnesian minerals are abundant. Now it will be clear that where the MgO-CaO criterion fails the $\text{K}_2\text{O-Na}_2\text{O}$ criterion holds most successfully, and *vice versa*. Thus, by combining the two criteria, it is found that a far higher degree of probability is established for or against a sedimentary origin. The double test holds for 76 per cent. of argillaceous rocks, and, applied conversely, it holds for 89 per cent. of igneous rocks.

Still another test is available, though of less value than the foregoing. There is qualitatively every gradation between granite and quartz-veins of igneous origin (silexite) on the one hand, and shales and pure quartz-sandstones on the other. Among sediments, however, a very high percentage of free silica (the residual silica or quartz of the norm) is more characteristic than it is among igneous rocks. If, therefore, a metamorphic rock is found to contain over 50 per cent. of normative quartz, there is good reason to suspect that the rock is of sedimentary rather than igneous origin.

Summing up, the chemical criteria favouring the derivation of a metamorphic rock from detrital sediments, and, in particular, from argillaceous types, are as follows:

1. Excess of Al_2O_3 (corundum of the norm).

If the excess be over 5 per cent. there is ground for suspecting a sedimentary origin, and this approaches certainty when the excess reaches 10 per cent. or more.

2. $\text{K}_2\text{O} > \text{Na}_2\text{O}$, combined with $\text{MgO} > \text{CaO}$.

Separately these criteria are not convincing, but together they establish a considerable degree of probability.

3. Very great excess of SiO_2 (quartz of the norm).

To count as evidence the excess should be greater than 50 per cent.

These criteria must always be applied with caution and with due consideration to every other scrap of evidence that can be brought to bear on the problem. Four series of difficulties arise which may occasionally lead to misinterpretation.

(a) In the preceding discussion it has been assumed that the parent rocks were of sufficiently distinctive composition to justify their diagnosis as sedimentary or igneous. This assumption cannot, however, always be made. Conglomerates of igneous-rock-pebbles would chemically fail to reveal a sedimentary origin. Unsorted and little-weathered deposits such as arkose would similarly provide evidence likely to lead to error. In such cases field associations must be relied on.

(b) Leith and Mead¹ point out that both weathered and hydrothermally-altered igneous rocks may come to have compositions akin to those of sediments. This possibility must certainly be recognised, but it is likely to be of only local occurrence, and need not be seriously considered when large areas of rocks are being dealt with.

(c) A third difficulty arises when metamorphic rocks are of composite origin, as in the case of injection-gneisses and types produced by contact-metamorphism accompanied by igneous exudations. Here ordinary chemical evidence will often fail.²

(d) The fourth difficulty arises out of the tacit assumption that during metamorphism itself, and independently of igneous exudations, the original chemical composition of the parent rock is not changed to any significant extent. In recent years this assumption has been questioned.³

¹ *Metamorphic Geology*, 1915, p. 227.

² For a discussion of a particularly refractory case see A. Holmes: *Q.J.G.S.*, 1918-19, p. 63.

See C. K. Leith & W. J. Mead: *loc. cit.*, and F. L. Stillwell: *Metamorphic Rocks of Adelie Land*, 1918, p. 72.

The loss of water, carbon-dioxide and other volatiles has long been recognised, but the detection of metamorphic diffusion and differentiation (leading to the production of peculiar rock types that are purely metamorphic and cannot be said to have an igneous, a sedimentary, or a composite origin) is just beginning. This is not the place to discuss these obscure and little-known phenomena, and it will suffice to say that they are essentially local, and that their recognition depends on a careful analysis of chemical data.

Leith and Mead conclude that on account of the above considerations chemical criteria fail to be decisive in the very cases where their help is most needed. This conclusion is undoubtedly too pessimistic, and it would be justified only if the study of a metamorphic formation depended on a single hand-specimen and a chemical analysis. Rocks have relationships with one another, and it is chiefly by the observation of their variations and associations, and by the general interplay of evidence and hypothesis that they can be made to yield their secrets. The structure of knowledge ultimately built up may be strong and of substantial worth, and it is within such a structure that chemical evidence, fortifying the weaker parts, finds its best application.

CHAPTER XI.

THE GRAPHICAL REPRESENTATION OF CHEMICAL ANALYSES.

Types of Diagrams.

The interpretation of chemical analyses often involves the study of long columns of figures, and, as is usually the case, relations of various kinds fail to disclose themselves clearly until the data are effectively set forth by a suitable method of graphical representation. From time to time different petrologists have devised different methods for expressing the relations between the constituents of igneous and other rocks, and for revealing the relations between series of genetically associated rocks. These methods, which may themselves be combined in various ways to build up more complex diagrams, are essentially of three kinds—

- (a) Diagrams representing single analyses by geometrical figures drawn according to a definite convention;
- (b) Diagrams representing analyses by a series of spots arranged with reference to rectangular co-ordinates;
- (c) Diagrams representing analyses or selected parts of analyses by single spots arranged with reference to trilinear co-ordinates, the axes here being taken as the three sides of a triangle (generally equilateral).

The second and third of these will be described in this

chapter with numerous examples to illustrate their application to specific purposes. The first type, however, being of little value, can be disposed of at once.

The representation of single analyses by diagrams has been discussed in some detail by Iddings,¹ and with special reference to the history of the subject. The most familiar type of diagram is that of Brögger. The percentages or molecular ratios of the eight dominant oxides are plotted on eight axes radiating from a point.² The same elementary method has been used with slight modification by Iddings.¹ Other single-rock diagrams, suggesting the mineral relations of some of the oxides, have been devised by Michel-Lévy and Mügge.

It does not appear to the author that these diagrams have sufficiently justified themselves to warrant their perpetuation. As pointed out by Pirsson³ twenty years ago, they provide nothing of significance which could not be added directly from the analyses themselves or, it may be added, from the norms calculated from those analyses. A comparatively young and rapidly evolving subject like petrology is almost necessarily strewn with the wreckage of suggestions that have led nowhere; and, in accordance with the rigorous process of evolution, the wreckage should periodically be cleared away from the path of study whereby the goal of the subject is approached. The author does not therefore propose to describe the diagrams referred to, for in many other books and papers they have already been given more prominence than they deserve as judged on the basis of effective contribution to the subject.

Variation-diagrams.

The second type of diagram has been most generally adopted by petrologists, and in its simplicity and fertility

¹ J. P. Iddings: *Igneous Rocks*, I, 1909, p. 14. See also *U.S.G.S. Prof. Pap.* 18, 1903.

² For examples see F. H. Hatch: *Text Book of Petrology*, I, p. 156.

³ L. V. Pirsson: *U.S.G.S. 20th Ann. Rep.*, Pt. 3, 1900, p. 571.

of suggestion it is unrivalled.¹ It is specially designed to draw attention to the relations between the compositions of rocks belonging to the same centre or region of igneous activity. In its simplest form, as illustrated by *Fig. 60*,

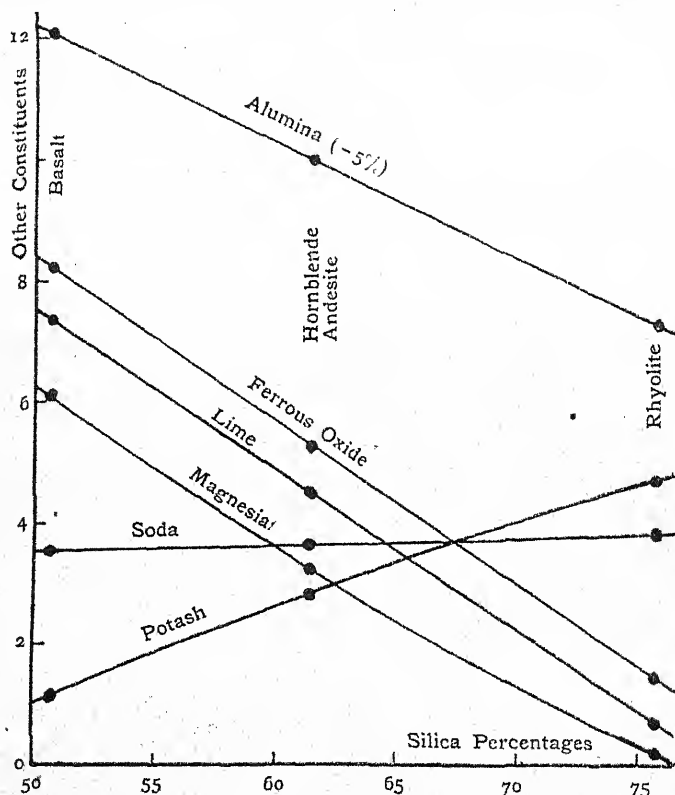


Fig. 60.—Linear variation-diagram of the volcanic rocks of Glen Coe.

it can be constructed by plotting percentages of oxides on squared paper. Percentages of silica are taken as abscissæ, and those of the other oxides are in each case plotted as ordinates. A single analysis is thus represented

¹ For the best general description see A. Harker: *Natural History of Igneous Rocks*, 1909, p. 118.

by a series of points on a vertical line, the position of the latter being determined by that representing the silica percentage on the horizontal axis. A series of analyses is therefore represented by points on a corresponding series of verticals. By joining up all the points representing the same oxide a line (straight, curved or crooked) is obtained which portrays the variation of that constituent throughout the series of rocks under investigation. The silica points are already plotted along the horizontal axis, and there is therefore no need to plot each one again as an ordinate. The result would be to give a straight line rising from left to right at a height which would generally be far above the other lines. Silica is taken to determine the abscissæ because of its relative abundance, because it enters into all the chief rock-forming minerals, and because it is the predominant acid constituent. For particular purposes other constituents or groups of constituents could be taken as abscissæ if desired. The general accuracy of the curves when drawn may be checked by the fact that on any vertical the sum of ordinates and abscissæ should approximate closely to 100.

Fig. 60 illustrates the variation of composition in the volcanic rocks of Glen Coe, the data being provided by analyses of three common types: rhyolite, hornblende-andesite, and pyroxene-andesite.¹ It provides an excellent example of *linear* variation, for clearly each oxide is a linear function of the silica percentage within the range of composition covered by the diagram. For convenience, all the iron is reckoned as ferrous oxide, for the particular state of oxidation assumed by the iron depends almost entirely on the minerals for which it is wanted. More often, however, the variation-lines are curved as in *Fig. 61*, some being convex upward (*e.g.*, alumina), some concave upward (*e.g.*, magnesia), and some inflected (*e.g.*, lime). A little consideration will show that if there are convex curves there must also be concave curves, one set of con-

¹ *Mem. Geol. Surv. Scot.*, 53, 1916, pp. 178-181.

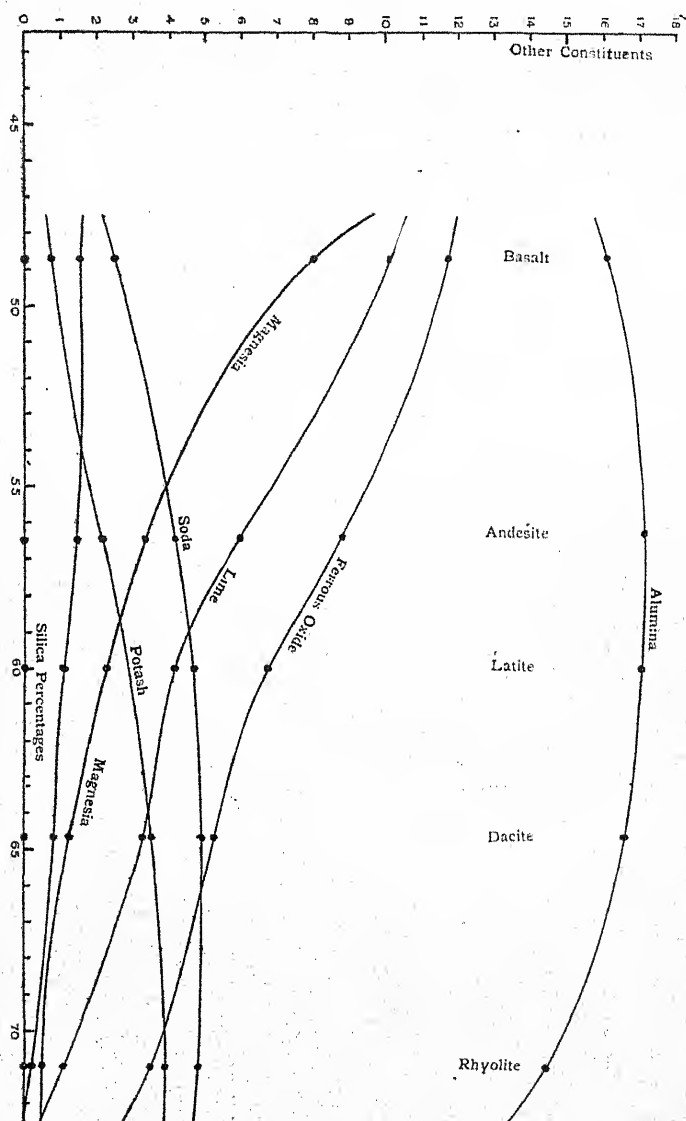


Fig. 6r.—Variation-diagram of the volcanic rocks of the San Franciscan volcanic field.

stituents declining as another rises. Within the silica range of most rock series the contrasted curves are those of alumina and the alkalis on the one hand, and those of magnesia and iron-oxides on the other. This obviously corresponds with the well-known fact that as the alkali-felspars decrease in amount, the ferromagnesian minerals increase. Moreover, corresponding to the double part played by lime, partly in felsic and partly in mafic minerals, the curve for lime is sometimes related to, or sympathetic with, one group of constituents, sometimes to the other, and occasionally it is inflected. The relations of the lime-curve to those of the alkalis are of especial interest and will be discussed in detail later.

Some rock series, such as those of Christiania and Madagascar, give irregular variation-curves, but even here the information revealed may be significant. To quote Harker, who has given us in his *Natural History of Igneous Rocks* a most illuminating account of variation diagrams: "If the analyses are numerous, and some of them fall near together, it may be found that the summits of the ordinates, for a given constituent, do not fall exactly on a flowing curve. This is a necessary consequence of imperfection in the analyses, and a certain degree of 'smoothing' is legitimate. More considerable discrepancies must be taken to indicate that the variation is not in fact wholly on one definite line, but is complicated by the effects of a subsidiary differentiation. In this way *the variation-diagram becomes a criterion* of the simplicity or complexity of the variation which it represents. Among the plutonic rocks of Christiania, Brögger at first ranked lardalite and akerite as co-ordinate with essexite, larvikite, and the rest; but he has since come to the conclusion that the first is a derivative from the larvikite magma, and the second is in like subordinate relationship to essexite. This might be inferred from the variation-diagram, where the inclusion of lardalite and akerite would necessitate some very unnatural flexures of the curves."

(See *Fig. 25*, p. 122, and *Fig. 26*, p. 123, in Harker's *Natural History*.)

Some authors plot their variation-diagrams in terms of molecular proportions instead of percentages. For certain purposes this is desirable but, in general, percentages give an adequate picture expressing the characteristics of a series of rocks in a very distinctive way. It is perhaps advisable to point out that in comparing one series of rocks with another the variation-diagrams should be both in percentages or both in molecular proportions, for the relative positions of the curves may be greatly changed in passing from one system of notation to the other.

Diagrams may also be drawn to show the variation of the standard minerals of the norm,¹ or of the actual mineral composition.²

Linear Variation-diagrams.

The linear variation of the volcanic rocks of Glen Coe is illustrated by *Fig. 60*. The lines for alumina, ferrous oxide, lime, and magnesia all follow the same general direction, and may be said to vary *sympathetically*. This suggests at once that the hornblende and pyroxene of the andesite and basalt are aluminous in general, for the alumina-curve is often flat or is beginning to descend towards the left between 60 and 50 per cent. of silica (cf. *Fig. 61*). The soda-line is nearly horizontal, and potash alone rises conspicuously with silica.

If only two analyses were plotted the lines joining the points would necessarily be straight, but there would be little reason to suppose that their prolongation would give almost exactly the analysis of a third rock. The probabilities are enormously against it; and the fact that even with three analyses a straight-line diagram is achieved indicates that the rocks concerned are related in an

¹ G. W. Tyrrell: *Trans. Geol. Soc. Glasgow*, xiv, 1912, p. 252, and Pl. xxix (Scottish Carboniferous basalts).

² G. W. Tyrrell: *Q.J.G.S.*, lxxii, 1917, p. 84 (Teschenite sill, Lugar).

unusually simple way. It would seem that the lavas owe their origin to a single continuous process of differentiation. Field evidence which would indicate the order of eruption is not available, nor, if it were, would the evidence throw much light on the mechanism of differentiation. Maufe states in the Survey Memoir (p. 106) that the extremely irregular arrangement of the basalts, andesites, and rhyolites indicates that they were supplied from neighbouring independent vents. We may therefore picture the process as follows: a magma occupying a more or less deep-seated cauldron differentiated continuously by the separation of crystals. These, being of greater density, would gradually sink through the magma, giving a composition gradient which would range from olivine-basalt below, through basalt and andesite to rhyolite, the latter representing the light residual liquor which would accumulate in the upper parts of the magmatic reservoir. From time to time eruptions would take place at different vents, and as these presumably would communicate with the reservoir at different levels, different lavas corresponding in composition to those levels would be formed. Obviously with such a mechanism order of eruption has no special significance. The general continuity of the differentiation combined with discontinuity of eruption would provide a great variety of possible types, all related, however, in the simple way represented in *Fig. 60*.

Some idea of the composition of the sinking crystals can be gained by assuming that the hornblende-andesite was formed from a basaltic magma having the composition of the basalt of *Fig. 60*. The only constituent likely to be little affected, if at all, by the abstraction of crystals is potash, as this must steadily accumulate in the residual magma. We may therefore adopt potash as a criterion of the proportion, x , of the parent magma which was removed by the sinking of crystals.

Let b be the percentage of any constituent in the basalt;

Let h be the percentage in the hornblende-andesite;

Let c be the percentage in the sinking crystals.

$$\text{Then } (1-x)h = b - xc.$$

Assuming that the crystals contain no potash and inserting the percentages of potash in the two lavas, we find

$$(1-x) \cdot 2.8 = 1.18,$$

whence, $x = 0.6$ (nearly).

The percentage of any other constituent is therefore given by substituting in the general formula

$$c = \frac{b - 0.4 h}{0.6}.$$

The composition of the crystals as calculated in this way is given in the table below together with the norm, which indicates that the composition is both possible and probable, the chief minerals being labradorite, augite, olivine and iron-ores. The separation of olivine is noteworthy as providing a means whereby a saturated or slightly undersaturated magma could become oversaturated above (owing to the concentration of silica) and undersaturated below (by accumulation of olivine crystals).

Oxides.	Percentages.	Molecular Proportions.			Norm. ¹	
SiO ₂ ...	46.3	...	727	...	Albite ... 30.8	} 67.2
Al ₂ O ₃ ...	18.5	...	181	...	Anorthite ... 36.4	
Fe ₂ O ₃ ...	6.7	...	42	...	...
FeO ...	4.2	...	58	...	Diopside ... 5.2	} 18.0
MgO ...	8.0	...	200	...	Enstatite ... 0.6	
CaO ...	9.2	...	164	...	Forsterite ... 12.2	
Na ₂ O ...	3.5	...	56	...	...
K ₂ O ...	—	...	—	...	Magnetite ... 7.0	} 14.1
H ₂ O ...	—	...	—	...	Ilmenite ... 4.9	
TiO ₂ ...	2.5	...	31	...	Hæmatite ... 2.2	
P ₂ O ₅ ...	0.2	...	2	...	...
MnO ...	0.2	...	2	...	Apatite ... 0.7	0.7

¹ Recalculated to 100.

Linear variation-diagrams are not common except over a comparatively short silica-range. A good example is given by Harker (*Natural History*, p. 140) illustrating the rock-series dunite—harrisite—allivalite—felspar-rock from Rum. The differentiated gabbros of Drum an Eidhne,

Skye (*ibid.*, p. 139), give a nearly linear variation over a wider silica range.

Variation-diagrams for Calc-alkali- and Alkali-series.

A thoroughly well-founded variation-diagram, for the lavas of the San Franciscan volcanic field, Arizona,¹ is reproduced in *Fig. 61*. The lavas constitute a simple and characteristic series, ranging from rhyolites through dacites, latites, and various types of andesites, to basalt and olivine basalt. The analyses available number 23, and all of them but one closely fit the curves. To avoid confusion the averages for each of the five types of lava have been plotted. As in the Glen Coe diagram ferrous oxide, lime, and magnesia decrease continuously as silica increases. Alumina, however, increases to a maximum at just over 60 per cent. of silica, and then declines. The alkalis each rise steadily, and are very perfectly sympathetic. Discussing these relations Robinson writes: "The continuity of the changes in amounts of the oxides is most striking in view of the fact that the chemical analysis of each lava was made on a single fragment representing the merest fraction of the entire rock mass to which it belonged. . . ."

"The serial chemical characters strongly support the inference that the lavas of the San Franciscan volcanic field are all genetically related, and are the differentiation products of a homogeneous magma from which they have been derived according to some law."

The series as a whole is one of characteristically calc-alkali type, though it has a slight peculiarity in the dominance of soda over potash throughout. Essentially similar series for which diagrams have been drawn are—

(a) the calc-alkali volcanic rocks of south-east Queensland,²

(b) the calc-alkali volcanic rocks of Mozambique,³ and

¹ H. H. Robinson: *U.S.G.S. Prof. Pap.* 76, 1913, p. 178.

² H. C. Richards: *Proc. Roy. Soc. Queensland*, xxvii, 1916, p. 105, and Plates vi-ix.

³ A. Holmes: *Q.J.G.S.*, lxxii, 1917-18, p. 264, and *Fig. 7*.

(c) the volcanic rocks of Lassen Peak, California.¹

In the last two of these the lime-curve is for the most part above the iron-oxide curve, and it begins to flatten and turn down to the left in positions corresponding to 55 and 50 per cent. of silica respectively. In the first and third potash exceeds soda when the silica percentage becomes high. Otherwise the general form of the curves is the same as in *Fig. 61*.

For comparison and contrast the diagram (*Fig. 62*) for a typical alkali-series occurring in Mozambique may be considered.² The series is characterised throughout by a high percentage of iron-oxides, and by an excess of soda over potash with a marked sympathy between the two inflected curves. Lime and magnesia occupy a low position on the right, but rise rapidly on the left in striking antipathy to the alkalis. The antipathy between alumina and iron-oxides is also noteworthy. In each direction the curves have been continued beyond the extreme analyses by what seems to be a natural extrapolation. On the left the potash-curve meets the base where silica = 38 per cent. The composition represented by this limit is that of a melilite-basalt. On the right the lime and magnesia curves meet the base where silica = 70.6 per cent., and the corresponding composition of the limit so established is that of an alkali-rhyolite. Although these two limiting rocks have not been found in Mozambique, they both occur in quite similar series of rocks in British East Africa and elsewhere, and are evidently natural members of the series, although occurring only where differentiation has proceeded to its extreme limits and where the magmas so produced were erupted as lavas.

Regarding the series as a whole, it seems doubtful—in the absence of any knowledge of the relative volumes of each rock-type—whether one is justified in regarding it as

¹ A. Harker : *Natural History of Igneous Rocks*, 1909, p. 126, *Fig. 28*.

² A. Holmes : *Q.J.G.S.*, lxxii, 1916-17, p. 266.

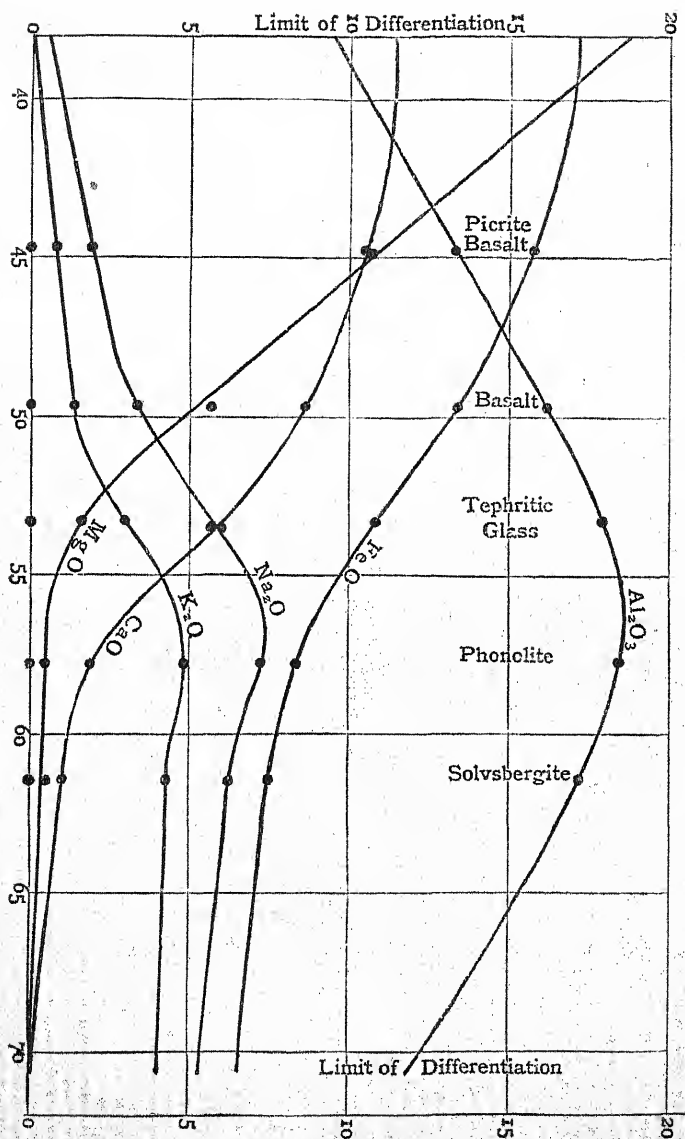


Fig. 62.—Variation diagram of the Tertiary volcanic rocks of Mozambique (alkali series).—(*Q.J.G.S.*, lxxii, 1916-17, p. 266.)

more "alkaline" than the calc-alkali series already described. The high alkalis on the right are compensated on the left by high lime and magnesia. The chief distinction, and it appears to be one of great significance, is that in alkali-series the antipathy of lime and magnesia is much more marked than in calc-alkali series. In the former (*Fig. 62*) the lime curve crosses the alkali-curves where silica = 54 per cent., whereas in the latter, as represented by the Mozambique example, this does not occur until silica has reached 66 per cent.

The Relation of Lime to Alkalies in Rock-series.

This contrast, as revealed by the two series of lavas in Mozambique, is so striking that it is worth while to examine other variation diagrams to see if it is of general application. The results of such an examination are listed below. The silica percentage is given in each case for the point where the lime-curve bisects the vertical distance between the soda- and potash-curves.

The contrast is evidently too general to be accidental, and is sufficiently marked to justify the conception of the

<i>Alkali-series.</i>			<i>Calc-alkali-series.</i>		
Magnet Cove ¹	...	45	Yogo Peak ¹	...	62
Teneriffe ²	...	52	San Francisco ³	...	62
B.E. Africa ²	...	52	Garabal Hill ¹	...	64
Abyssinia ²	...	53	Glen Coe ⁴	...	65
Mozambique ²	...	54	Mozambique ²	...	66
Réunion ²	...	55	S.E. Queensland ⁵	...	66
Christiania ¹	...	57	Lassen Peak ¹	...	68
<i>Average</i>	...	53	<i>Average</i>	...	65
Harker's generalised			Harker's generalised		
curves ¹	...	50	curves ¹	...	65

¹ A. Harker: *Natural History of Igneous Rocks*, 1909, pp. 122-151.

² A. Holmes: *Q.J.G.S.*, lxxii, 1916-17, pp. 268-269, *Fig. 8*.

³ H. H. Robinson: *loc. cit.*, and p. 449 of this book, *Fig. 61*.

⁴ This book, p. 443, *Fig. 60*.

⁵ H. C. Richards: *Proc. Roy. Soc. Queensland*, xxvii, 1916, p. 189, and Plates vi-ix.

In the alkali-series of Queensland crossing has not occurred at 57 per cent. of silica, beyond which there are no data.

two very different suites of rocks described as *Atlantic* and *Pacific*, or as *alkali* or *calc-alkali*. Geographical terms have not been successful in this connection, and the chemical terms are equally unhappy in their suggestion of a half-truth, but far more important than the nomenclature is the conception itself which lies at the heart of the problem of petrographic provinces.¹

The question now arises as to the possibility of intermediate series. The difficulty that has sometimes arisen in trying to decide whether a given series should be allocated to the "Atlantic" or "Pacific" suite indicates the likelihood. The Arctic province,¹ represented most completely in analyses by Iceland lavas, may be taken as an example. To avoid misconception it must be pointed out that basalts and rhyolites are the most abundant groups represented, andesites and trachytes being rare. The curves are, nevertheless, justified by the analyses available. It will be seen that the diagram differs in certain respects from those already discussed, but the sudden change of slope in the antipathetic curves for lime and the alkalis where they cross recalls the alkali-series. In calc-alkali series this marked change of slope does not normally occur. On the other hand, the petrographic types are not alkali-rocks except in the case of some of the rhyolites. Corresponding to this difficulty in placing the series, the lime-alkalies crossing takes place where silica=61.5 per cent. The intermediate characteristics of the Arctic province are corroborated by the rocks of centres other than Iceland, and consistently with the recognition of this fact it is interesting to notice that the region lies between the well-marked alkali-province of the Mid-Atlantic Islands and the equally well-marked calc-alkali province of the Pacific borders.

Now in the list on p. 452 there appear two calc-alkali series in which the lime-alkalies crossing takes place where silica=62. It is therefore to be expected that these series,

¹ See *Min. Mag.*, xviii, 1918, p. 220, for further discussion.

like those of the Arctic, should give at least a hint of alkali-associations. True to deduction the calc-alkali series of Yogo Peak and the San Franciscan field have each produced alkali-types at their differentiation limits; the former a *shonkinite* and the latter a *riebeckite-rhyolite*.

Pursuing the matter still more closely, we find among the alkali-series a crossing at 57 for the Christiania rocks. This high figure is obtained from Harker's *Fig. 26*, from which laurdalite has been omitted. As a consequence the series actually represented is by no means strongly "alkaline." In his *Fig. 25*, in which laurdalite is included, the crossing takes place, not at 57, but at 52.

At the other extreme of the alkali-series the Magnet Cove figure, 45, demands attention by being well below the average. We should therefore expect the rocks to be alkali-types of a very conspicuous kind. The types actually represented in Harker's *Fig. 31* are jacupirangite, ijolite, arkite, and foyaite, all richly felspathoidal rocks.

The position of the lime-alkalies crossing is thus found to be of critical importance in comparing rock-series, for it serves in a general way to correlate certain characters belonging to series as such and not merely to individual rocks.

The Representation of Petrographic Provinces.

In a recent paper by F. D. Adams a so-called three-dimensional representation of the rocks of a petrographic province is described.¹ Each rock is represented by a diagram of the type shown in *Fig. 61*, where ordinates at equal distances apart represent the different constituents, the adjacent points being connected by straight lines. The diagrams are then cut out and placed vertically one behind another at equal distances apart in order of silica percentage. The spaces between the successive sheets are then filled in with plaster of Paris and a solid model results. F. F. Grout² has adopted the principle, but

¹ *Journ. Geol.*, xxii, 1914, p. 689.

² *Journ. Geol.*, xxvi, 1918, p. 622.

plots the norm instead of oxides, and prefers to clamp the diagrams together so that they are left free to be arranged at will according to the aspect from which it is desired to study them.

These models are three-dimensional, certainly, but as diagrams they are not even two-dimensional except in a distorted way. No physical meaning can be attached to lines joining SiO_2 to TiO_2 , TiO_2 to Al_2O_3 , and so on. In the third dimension of the model the peaks representing percentages of the same constituent provide points for the ordinary variation-lines, but, instead of being placed at equal distances apart, they would require to be placed at distances proportional to the silica-percentages. To place them at equal distances has no physical meaning.¹ It is felt, therefore, that Adams has not succeeded in his attempt "to secure a more satisfactory expression of the chemical relations," and that neither his percentage-model nor Grout's normative model can compare favourably with the much simpler but analytically more powerful variation-diagram.

As an example of the representation of several petrographic provinces by variation-diagrams let us consider *Fig. 63*, which was drawn to demonstrate the similarity of the Mozambique alkali-series to that of certain other areas. To prevent confusion the curve for each constituent is drawn separately on a silica-base, which is repeated six times horizontally for the six constituents plotted. The curves for the same constituent as represented in the five different areas are placed in vertical columns so that they can be compared at a glance.

It will be seen that in each case there is a strong family likeness. The chief points of dissimilarity are found in

¹In a variation-diagram devised by Pirsson (*U.S.G.S. 20th Ann. Rep.*, Pt. 3, 1900, p. 571, and J. P. Iddings: *Igneous Rocks*, I, 1909, p. 11, and *Fig. 2*) abscissæ are taken at equal distances apart, because this happened approximately to represent the distances between the samples analysed in a single differentiated body of rock. Here there is, of course, a very definite physical meaning, and the diagram turned out to be linear.

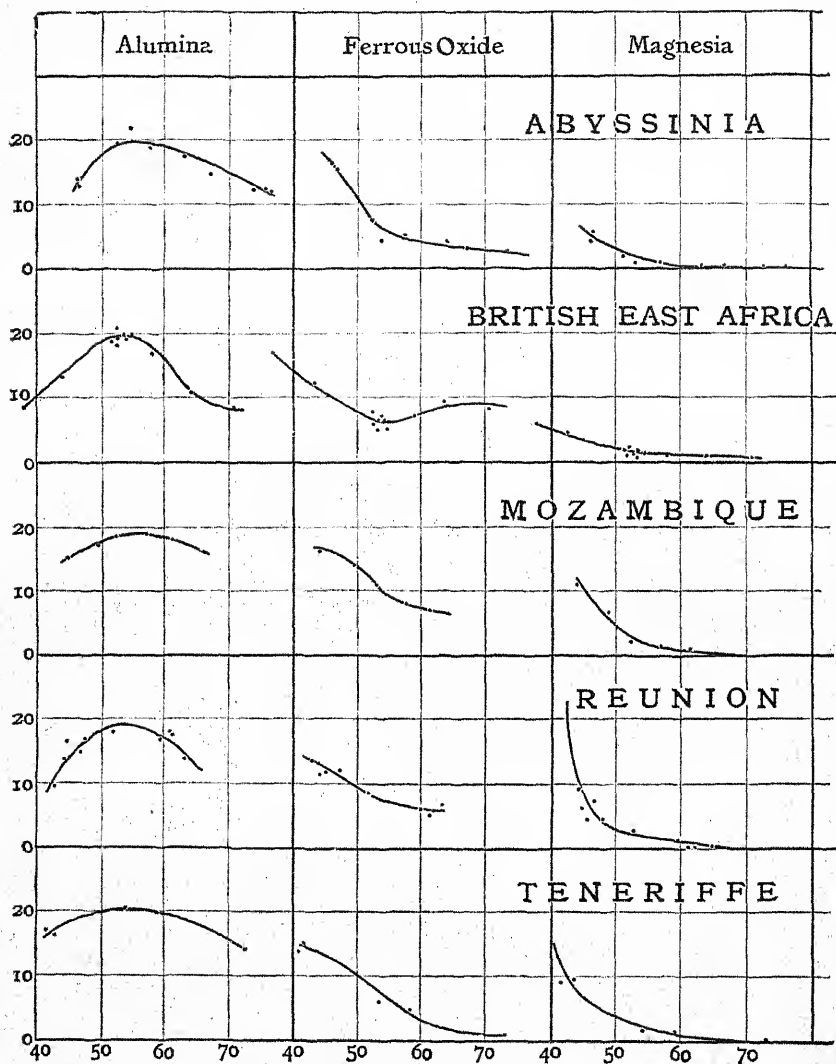
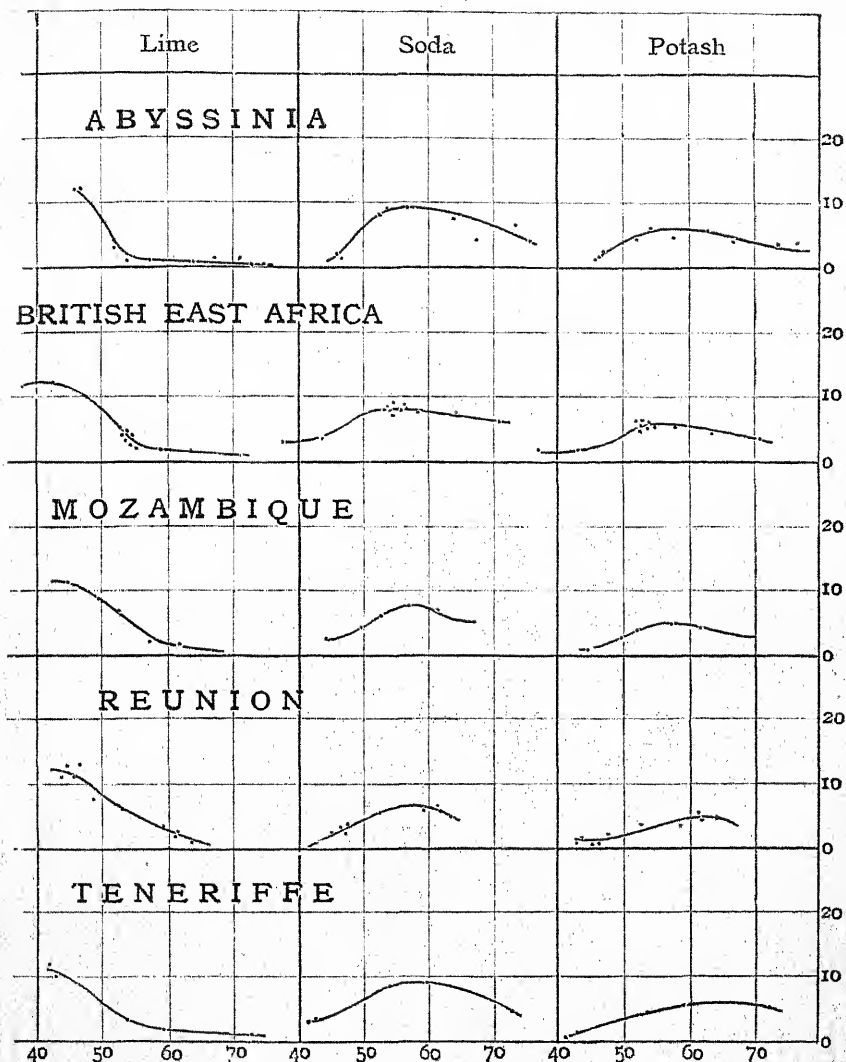


Fig. 63.—Variation-diagrams of the Tertiary volcanic rocks (alkali series)
(*Q.J.G.S.*, lxxii, 1916-17,



of Abyssinia, British E. Africa, Mozambique, Reunion and Teneriffe
pp. 268-269).

British East Africa, where, as Harker has already pointed out,¹ alumina falls rapidly in the more siliceous rocks, and iron-oxide (largely ferric) instead of gradually declining compensates for the low alumina by ascending antipathetically. Mineralogically, this means the replacement of the union of alumina and soda in albite and nepheline by that of ferric iron and soda in the soda-pyroxenes and amphiboles. The magnesia-curve for the rocks of British East Africa also differs from the others in its slow ascent on the left. The discrepancy is here due to subsidiary differentiation among the basic rocks, for melilite-basalts and picrite-basalts occur which, if analysed, should provide a normal magnesia curve.

The resemblances of the curves for Abyssinia, Mozambique, and Teneriffe are very striking, and they evidently indicate that similar processes acting on similar deep-seated materials have achieved similar results in three widely-separated provinces.

Analyses of the alkali-rocks of Madagascar, the Transvaal, Angola, and the Los Islands were also plotted, but in none of these cases was there any resemblance to the Mozambique curves, probably on account of the existence of more than one series of differentiated rocks in those districts.

Special Types of Variation-diagrams.

In investigating rock-series the principle of the variation-diagram can often be used to test and illustrate specific relations. Three examples will be discussed—

- (a) The antipathy between titanium dioxide and felspars in the saturated basalts of the Brito-Arctic province.
- (b) The antipathy of ferric and ferrous oxides in slates and its bearing on the colours of the latter.
- (c) The change of composition involved in the process of albitisation.

¹ A. Harker: *loc. cit.*, p. 124.

(a) *Titanium Dioxide and Felspars.* — As shown by Fig. 64, a high content of titanium dioxide is a characteristic of the basalts of Iceland, as indeed it is for all the basaltic rocks of the Arctic province. The constituent

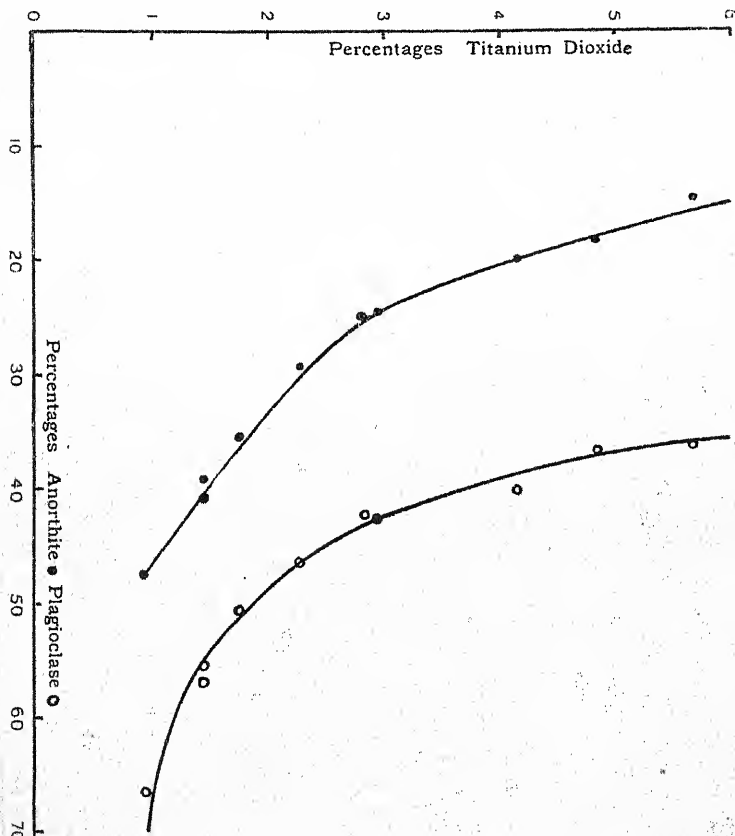


Fig. 64.—Diagram to represent the antipathetic relation between titanium dioxide and normative anorthite or normative plagioclase in the basalts of the Brito-arctic province.

is present chiefly as ilmenite or titaniferous magnetite, and is more abundant in saturated basalts (*i.e.*, those free from olivine) than in the undersaturated basalts (*i.e.*, those con-

taining olivine). Considering only the former series it is found that those with phenocrysts of plagioclase contain less titanium dioxide than those of uniform grain, suggesting that the phenocrysts dilute the rock as a whole. Conformably with this view it is remarkable that in a general way titanium oxide varies inversely as the plagioclase feldspar in the uniformly-grained rocks, whereas the relation holds for porphyritic rocks only if the feldspar phenocrysts are left out of account. The antipathy between titanium dioxide and normative anorthite and plagioclase is illustrated by the adjoining table and diagram, *Fig. 64*. The only exception is the Scoresby Sound basalt, which has too much feldspar (on account of the presence of phenocrysts) to fit into the scheme.

<i>Locality.</i>		<i>Titanium dioxide.</i>	<i>Normative Anorthite.</i>	<i>Normative Plagioclase.</i>
Hare Island	...	5.68	14.65	36.13
Farøe Islands	...	4.83	18.35	36.69
Iceland	...	4.17	20.02	40.46
Scoresby Sound	...	3.98	(37.53)	(51.15)
Spitzbergen	...	2.93	25.30	42.59
Mull	...	2.80	24.63	42.42
Franz Josef Land	...	2.29	27.24	46.63
Kuzkin Island	...	1.63	35.58	51.30
Mull	...	1.46	38.92	59.36
Mull	...	1.46	40.87	61.83
Mull	...	0.93	47.82	66.16

Between actual feldspars and titaniferous iron-ores the same relation holds for all the basalts of which the mode has been determined. It is interesting to notice that the same antipathetic relation is exemplified by the highly titaniferous saturated basalts of Pantelleria and the other islands of the same province. The relation is clearly of genetic significance. In all these rocks plagioclase had almost completed its crystallisation while the bulk of the titanium dioxide was still in solution. The idea thus suggests itself that the basalts are all derivatives from a common regional type of magma in which a precisely

similar process of partial separation between felspars and residual liquor everywhere took place.¹

(b) *Iron Oxides in Slates, etc.* — The relation of the colours of slates, shales and other sediments to the ratio of ferric and ferrous iron has been studied by Tomlinson.² He has collected the following figures from various sources :—

Colour.	Ratio of Fe^{III} to Fe^{II} in			
	Slates.	Spotted Slate.	Shales.	Sandstones.
Red	3.91	2.42	2.72	3.02
Purple	2.22	1.31	1.78	—
Green	0.23	0.93	—	0.89
Black	0.13	—	—	—

The data are expressed in a very striking way by the method of *Fig. 65*. Ferric iron is plotted vertically against ferrous iron horizontally, and radiating lines are then drawn from the origin to separate groups of points representing rocks of different colour. A few additional figures have been added to those compiled by Tomlinson. A line at 45° through the origin, representing all points for which $Fe^{III} = Fe^{II}$, separates the red and purple slates and shales (with more ferric than ferrous iron) from the green and black slates and shales (with more ferrous than ferric iron). Corresponding to the higher state of oxidation the red and purple slates contain no carbon, and the black carbonaceous slates are thus confined to that part of the diagram representing an excess of ferrous iron. The diagram also shows that slates become red only when Fe^{III} exceeds $2Fe^{II}$, and that a green colour is developed only³ when Fe^{II} exceeds $2Fe^{III}$.

In *Fig. 66* the same relation is brought out by a variation diagram of a more familiar type. Ferric oxide and

¹ A. Holmes : H. F. Harwood : *Min. Mag.*, xviii, 1918, p. 215.

² C. W. Tomlinson : *Journ. Geol.*, xxiv, 1916, p. 160.

³ The one apparent exception is not a slate, but a sandstone.

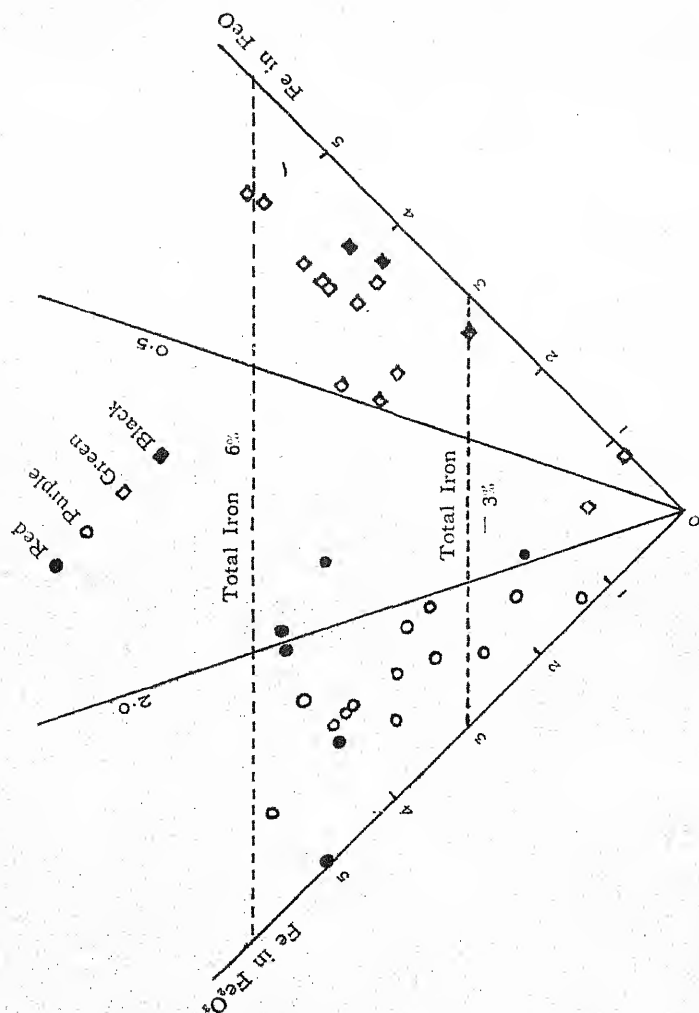


Fig. 65.—Diagram to show the correlation between the ratio of ferric to ferrous iron and the colours of slates. Cf. Fig. 66.

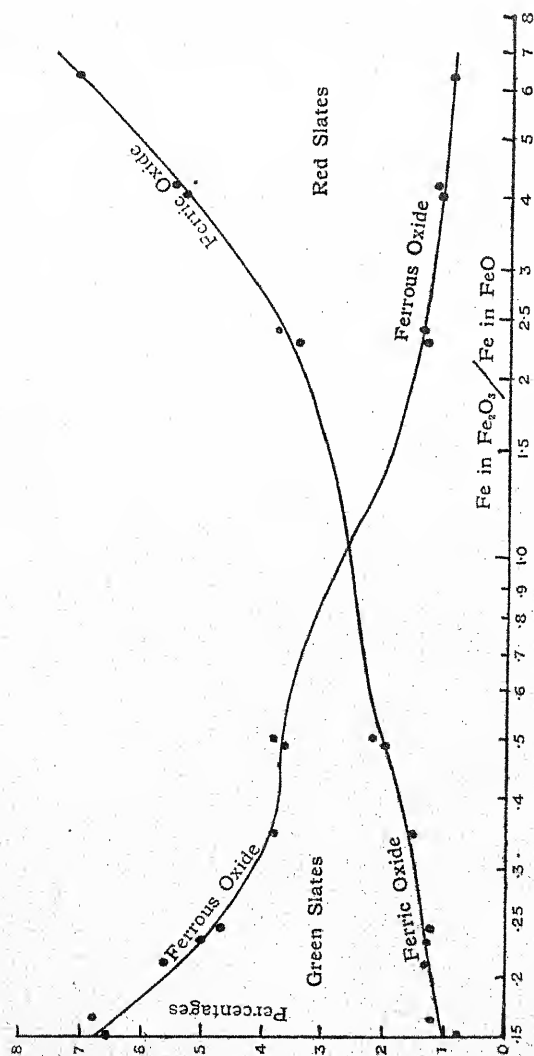


Fig. 60.—Diagram to show the correlation between ferrous and ferric oxides and the green and red colours respectively of slates.

ferrous oxide in the slates of Vermont¹ are plotted (as percentages) with the $Fe''' : Fe''$ ratios as abscissæ. When ratios are used as abscissæ or ordinates it is often desirable to employ a logarithmic scale. In this case the point "1" representing $Fe''' = Fe''$ is placed in the middle of the base-line and ratios larger and smaller are measured off by distances proportional to their logarithms. As $\log. 1 = 0$, this is a convenient starting-point. The diagram is thus divided into two equal parts, with green slates on the left and red on the right. The antipathy of the ferric and ferrous oxides is well brought out, but, while this feature is general, it must be observed that the actual curves are valid only for the red and green Vermont slates, which evidently constitute a single serially related group. In other series the total percentage of iron oxides may be very different and the points therefore fall in positions departing from those of the curves in *Fig. 66*.

(c) *Formation of Adinole*.—The albitisation of shale to adinole has been demonstrated by Mr. H. Dewey² by means of a variation-diagram, which is here reproduced in a modified form (*Fig. 67*). Analyses of adinole and the unaltered shale from which it was derived are plotted on a silica-base as usual. Now since the process of forming adinole from shale clearly involves the transference of material from the igneous rock to which the metamorphism is due, it ought to be possible to form an estimate of the composition and quantity of the added material. In the diagram the composition of the added material must lie on a vertical to the right of the adinole, since the latter must lie between the added material and the shale. Moreover, the variation-lines for each constituent must be straight. These lines are already determined by the two known analyses and their prolongation to the right must somewhere give the required composition. The exact vertical

¹ T. N. Dale: *U.S.G.S. Bull.* 275, 1905, p. 34.

² H. Dewey: *Trans. Roy. Geol. Soc. Cornwall*, xv, 1915, p. 75, and *Fig. 2*.

to be taken cannot be determined exactly, but a limit is provided by the fact that the lime- and magnesia-lines reach the base where silica=68.5 per cent. The required composition therefore cannot be

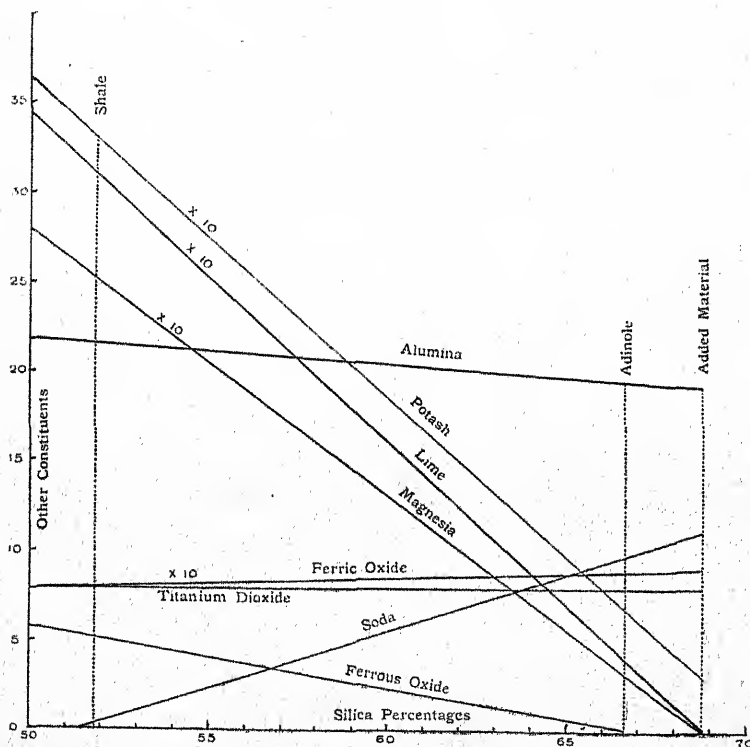


Fig. 67.—Linear variation diagram to illustrate the formation of adinole.
Note.—To avoid confusion, the percentages of several of the oxides are multiplied by 10.

far from that given by the vertical through this point. The percentages of the added material determined graphically in this way are set out below, together with the corresponding norm. This shows at once that the process involved the addition of albite (with a very little ortho-

clase), together with small amounts of iron and titanium oxides, and quartz.

	Percentages.	Molecular Proportions.	Norm.	
SiO ₂	68.5	1142	Quartz	2.3
Al ₂ O ₃	19.2	188	Orthoclase	1.7
Fe ₂ O ₃	0.9	—	Albite	94.8
FeO	none	—		
MgO	none	—	Titaniferous iron-ore	1.7
CaO	none	—	<i>Note.</i> —The alumina left over amounts to only 0.4 per cent., an amount well within the experimental error of the method.	
Na ₂ O	11.2	181		
K ₂ O	0.3	3		
TiO ₂	0.8	—		

Dewey arrives at the same result by assuming that albite was added, and noticing the discrepancies produced by drawing variation lines on that assumption. He goes on to say: "Most analyses show that such an addition occurred, and this is a fact of first-class importance when the physical properties of artificially produced albite felspar are remembered. In the experiments conducted by Messrs. Day and Allen on the melting or crystallising points of the felspars great difficulty was experienced in determining that of albite because, although a melt was easily obtained, this melt remained in a glassy or viscous state over a wide range of temperature. When, however, a small quantity of magnetite was added, a mobile liquid was formed in which crystallisation readily took place."

The diagram, *Fig. 67*, also gives an estimate of the quantity of the material added. If A represents the added material, M the adinole (mixture of A and S) and S the shale, then

$$(a+s)M=(m+s)A+(a+m)S,$$

where a, m, and s represent the silica percentages of A, M, and S respectively. By measurement, we find that to the original shale over six times its weight of the albite-

titaniferous magnetite solution must have been added in order to produce the adinole.¹

Variation-diagrams based on Molecular Proportions.

It has already been mentioned that molecular proportions of constituents are sometimes plotted in place of percentages. The variation-diagrams so produced may bring out mineralogical relations more directly than when percentages are used, and with the object of developing this advantage to its maximum Dr. J. W. Evans has devised two modified types of diagrams of which descriptions will now be given.

In the first of these, appropriately called the *alumina-diagram*, the molecular relation of alumina to the sum of the alkalis and lime is displayed. The molecular proportions of potash are first plotted on a silica-base in the usual way. Above the potash-line soda is plotted additively, and above the resulting line, which represents the sum of the alkalis, lime is plotted. The third line thus gives the variation of alkalis plus lime. Starting again from the base-line alumina is plotted, and the interest of the diagram lies in the relation of the alumina-line to the third of those previously drawn. Where the alumina-line rises above the latter the presence of normative corundum is revealed, and where it falls below the potash-plus-soda-line normative acmite is indicated. More generally the alumina-line lies somewhere in the space representing lime, and the proportions of lime in anorthite and lime in diopside (or wollastonite) are brought out by its relative position.

Figs. 68 and 69 alumina-diagrams have been drawn for hypothetical series of average calc-alkali-rocks and average

¹ For a diagram illustrating the progressive alteration of porphyry by hydrothermal solutions see F. L. Ransome: *U.S.G.S. Prof. Pap.* 75, 1911, p. 97.

Diagrams representing the relative gains and losses of constituents in rocks that have suffered weathering, metamorphism, or other alteration see C. K. Leith & W. J. Mead: *Metamorphic Geology*, 1915, pp. 288 and 291.

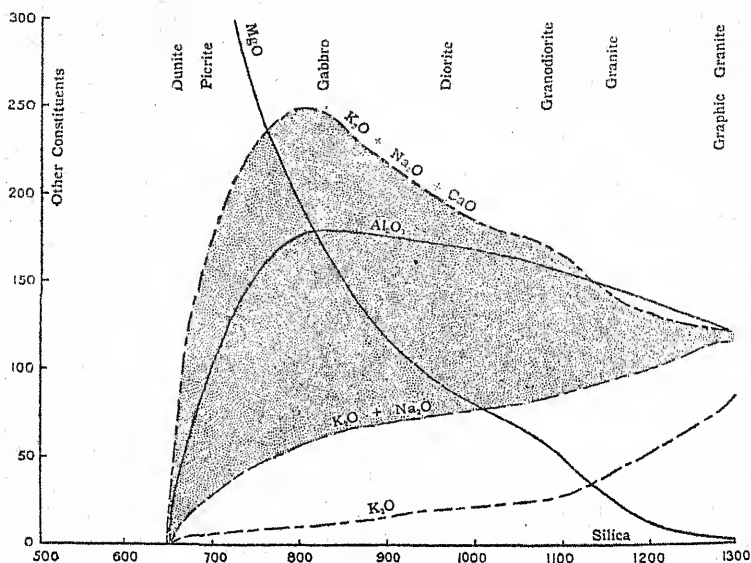


Fig. 68. — Alumina diagram (calc-alkali series).

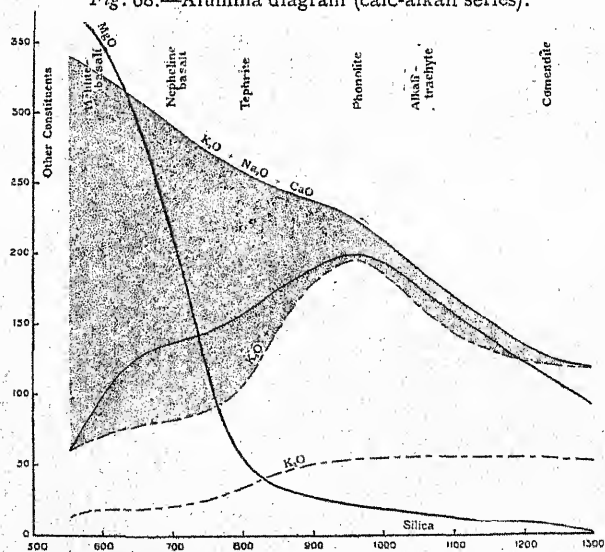


Fig. 69. — Alumina diagram (alkali series).
 Lower curve of shaded area represents $\text{K}_2\text{O} + \text{Na}_2\text{O}$.
 Median curve represents Al_2O_3 .

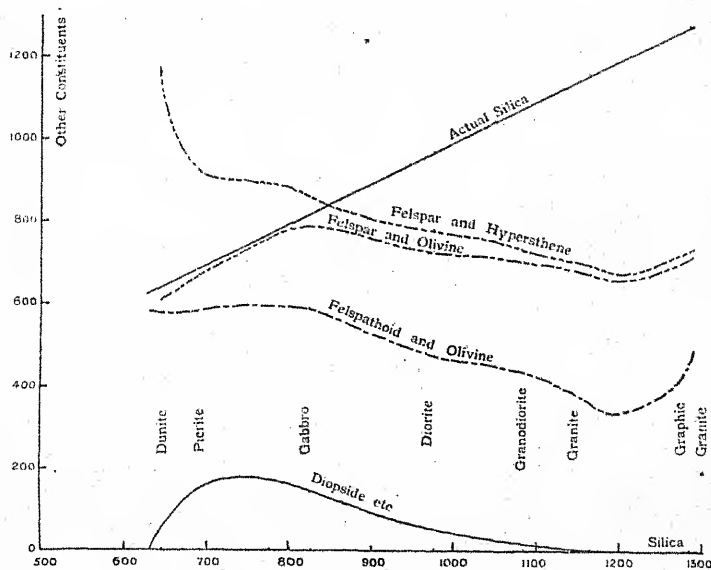


Fig. 70.—Silica diagram (calc-alkali series).

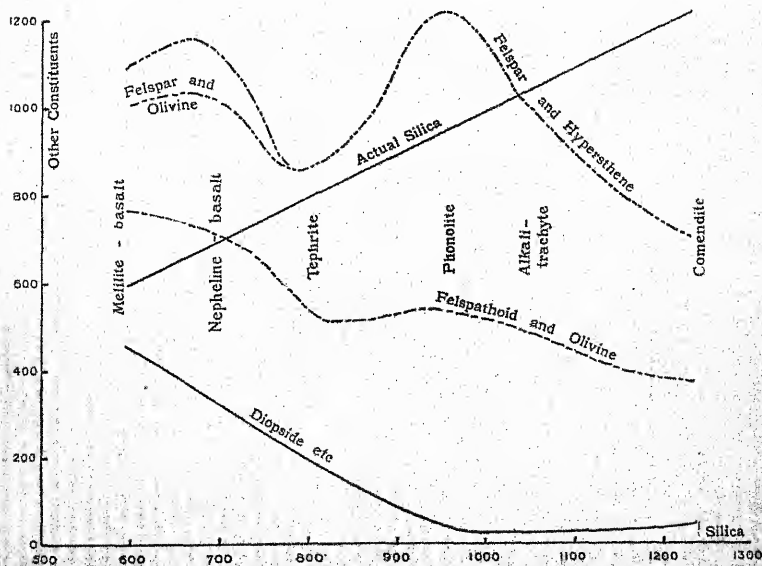


Fig. 71.—Silica diagram (alkali series).

alkali-rocks respectively. The average analyses plotted are those computed by Daly and published in Chapter II. of his *Igneous Rocks and their Origin*. It will be seen that normative corundum (representing mica chiefly) appears in the neighbourhood of granite, and that normative acmite (representing ægirine or riebeckite chiefly) appears in the neighbourhood of comendite. Elsewhere the alumina-line lies inside the lime-area, which is shaded. The funnel-like shape of the lime-area in each diagram is worthy of notice. In each case the neck of the funnel is reached when the alkalis are at their maximum, but while this point is reached in *Fig. 68*, where silica is nearly 1300, in *Fig. 69* it is reached where silica is 960. This difference of behaviour corresponds with the relation between lime and alkalis discussed on p. 452.

In the second set of diagrams (*Figs. 70 and 71*) the degree of silica-saturation is brought out. From the molecular proportions various simple calculations are made on the principle of the norm. The silica necessary for the invariable standard minerals, such as diopside, acmite, and wollastonite, is first determined, and is plotted on a silica-base as before. Above the curve so obtained three further curves are drawn representing—

- (a) the silica necessary to form feldspathoids and olivine;
- (b) the silica for feldspars and olivine; and
- (c) the silica for feldspars and hypersthene.

The actual amount of silica is then plotted from the base, and necessarily gives a straight line.

The intersection of this line with the curves previously drawn is here the point of interest. Where the actual silica-line is above (c) normative quartz is present. Where it lies between (c) and (b) olivine is indicated, and when it falls below (c) feldspathoids and olivine (normative).

In *Fig. 70* normative quartz is present almost to

gabbro, but beyond, the olivine-area is traversed and the line just fails to penetrate the feldspathoid- (and olivine-) area below. In *Fig. 71*, however, the silica-line penetrates the feldspathoid-area just past the alkali-trachyte, no intervening olivine-area being present. Before reaching nepheline-basalt the line drops below the feldspathoid-curve, indicating the presence of normative calcium orthosilicate with or without kaliophilite. This becomes very marked when the melilite-basalt is reached, and corresponds with the extremely basic character of the mineral melilite and the rocks in which it occurs.

The silica- and alumina-diagrams together enable one to recognise and distinguish two main types of alkali-rocks—

- (a) those in which "alkalinity" is due to relative deficiency of alumina, soda pyroxenes and amphiboles then being present; and
- (b) those in which "alkalinity" is due to relative deficiency of silica, feldspathoids then being present.

Normatively, these tests both fail to bring out any particular feature in virtue of which the trachyte of *Figs. 69* and *71* could theoretically be considered to justify its prefix "alkali-." The reason for this is partly that the soda-pyroxenes and amphiboles may themselves contain alumina, and partly because if biotite be present more alumina is necessary to satisfy the potash than is calculated in the norm or shown in the diagram. For this reason acmite is frequently absent from the norm when it is actually present in some form or other in the mode. The actual mineral composition remains, therefore, the best guide to the nature of a rock, and the two tests of silica-saturation and alumina-saturation are of valuable assistance in distinguishing alkali-rocks from calc-alkali rocks with a reasonable degree of sharpness. There is no longer

any reason for the reproach that the decision whether or not a given rock is an alkali-type depends on the taste and personal bias of the observer.

Trilinear Co-ordinates.

Hitherto the diagrams represented have been built up with reference to rectangular co-ordinates. When it is desired to bring out the relations between, or the correla-

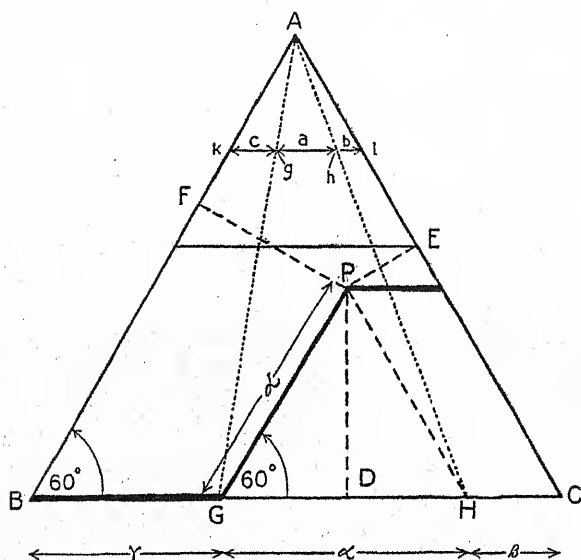


Fig. 72.—Trilinear co-ordinates: the representation of three variables, a , b , c , by a point P .

tion of, three constituents or other variables taken together, trilinear co-ordinates may be used. Any three variables can be represented by a single point in a triangle, the point having the property that its distances from the three sides are proportional to the amounts of the three constituents. The point may be regarded in each case as the centre of gravity of the triangle, the masses of the three constituents or variables being supposed to be concentrated at the three corners.

A.—One of the simplest methods of determining the position of the point P, which shall represent the three constituents a, b, and c, is demonstrated in *Fig. 72*.

Recalculate the amounts of a, b, and c to percentages of the total, $a+b+c$. Let the percentages be α , β , and γ . The base BC of the equilateral triangle ABC having been divided into 100 parts, mark off γ from B, and from the point G so found set off α at 60° , *i.e.*, along a line parallel to AB. The point P is then determined.

Proof.—From C mark off β and thus determine the point H. Obviously $GH = \alpha$. Now PGH is an equilateral triangle, each of whose sides has a length equal to α on the scale used. The length of the perpendicular PD dropped from P to the base BC is therefore $\frac{\alpha}{2}\sqrt{3}$. Similarly the per-

pendicular PE from P to AC is $\frac{\beta}{2}\sqrt{3}$, and PF is $\frac{\gamma}{2}\sqrt{3}$.

Hence the perpendiculars from P to the sides are proportional to the amounts of a, b, and c. Conversely if the point P is known it is easy to determine the percentages of the three constituents which it represents. This is often useful in studying diagrams like *Fig. 72*.

In practice the points G and H may be graphically determined without recalculating to percentages to find α , β , and γ . Find the horizontal line kl having the length (to scale) $a+b+c$. Along this mark off distances representing c and a, starting from the left. Through the points g and h so determined draw lines from A to the base. By similar triangles it is easy to prove that the three divisions of the base BC made by the points G and H give the required percentages. This method may, of course, be used for assessing any number of constituents in terms of percentages, *i.e.*, to a total of 100, or to any other total that may be required.

B.—Another very simple method of finding the required point P, also without recalculating to 100, is illustrated by *Fig. 73*. The three constituents are here

taken in pairs. Starting with a and b , a line kl parallel to AB is found having the length $a+b$. Marking off a length a from l the point q is determined, and the line CqQ is then the locus of all points representing the ratio of a to b . Similarly find a line mn parallel to AC having the length $a+c$, and determine the point r . The intersection of the line BrR with CQ determines the required point P .

To carry out these constructions easily and rapidly it is desirable to have a supply of triangles prepared with the

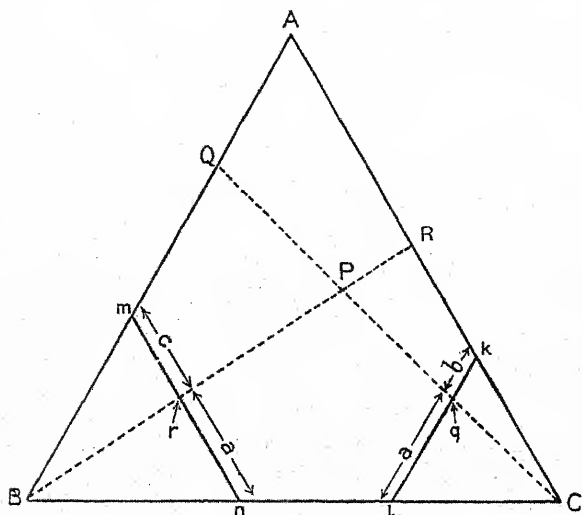


Fig. 73.—Trilinear co-ordinates.

sides divided into 100 parts and lines drawn through each point parallel to the sides. They can readily be produced by the use of one or other of the many duplicators now available.

C.—Another method, in which ordinary squared paper can be used, depends on the use of median-lines as subsidiary co-ordinates, and was that first adopted by Becke, and since extensively employed by Osann. The method of determining the required point is essentially that of finding the centre of gravity of three masses a , b , c , concentrated at the points A , B , C .

Construct the medians BD and CE and take them as axes with O as origin. The method is easily applied to any triangle, but, as suggested by Dr. J. W. Evans, the work of plotting is greatly facilitated by constructing the triangle on squared paper as shown in *Fig. 74*. OB then is equal to OC, and each may be divided into, say, 10 equal parts.

Let P be the required point (centre of gravity) representing the three constituents, and let x and y be the co-ordinates of P. Then, following the centre-of-gravity analogy, we may equate the moments about the median CE to determine x , and equate those about BD to determine y .

Thus, $x(a+b+c) = 10b - 10a$;

and $y(a+b+c) = 10c - 10a$;

giving $x = \frac{10(b-a)}{a+b+c}$; and $y = \frac{10(c-a)}{a+b+c}$.

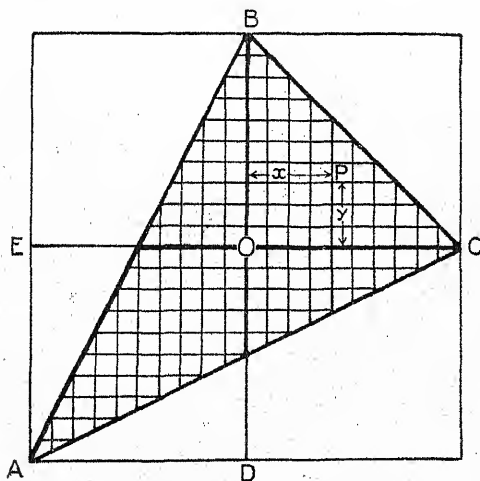


Fig. 74.—Trilinear co-ordinates, using squared paper.

One or both results may be negative, and they are then plotted in the appropriate quadrant.

In interpreting trilinear diagrams it must be thoroughly understood that—

- the distance of P from BC gives the percentage of A;
- the distance of P from AC gives the percentage of B;
- the distance of P from AB gives the percentage of C.

Thus, if P should fall on one of the sides of the triangle, say, BC, then A is absent, the percentage of B is given by CP (not BP) and that of C is given by BP. Consistently with the convention that a constituent is concentrated at a corner and there represents 100 per cent., the opposing side repre-

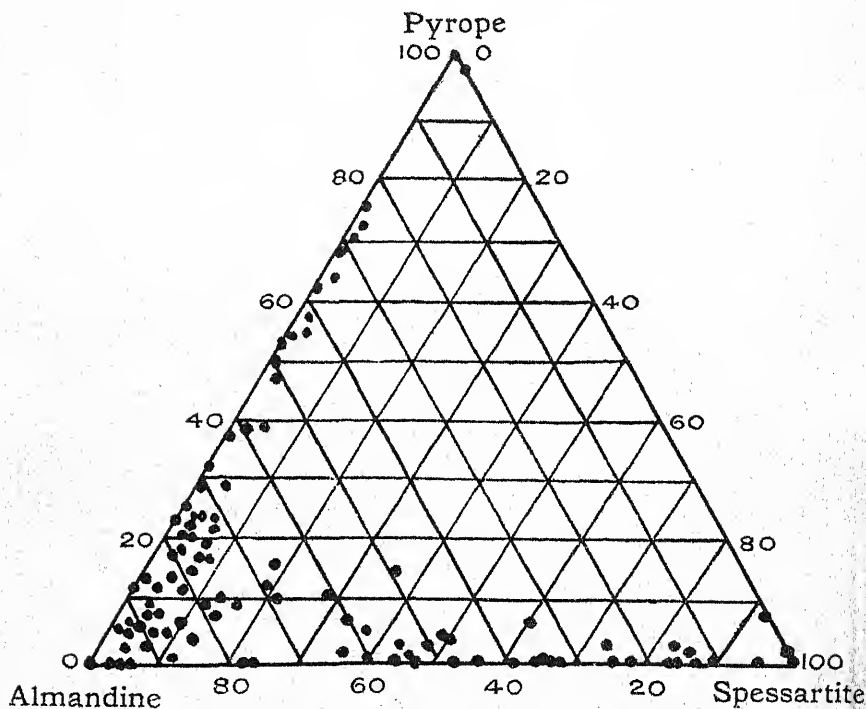


Fig. 75.—Triangular diagram to show the absence of isomorphism between spessartite and pyrope.

sents 0 per cent., and intermediate positions represent percentages measured from that side.

Examples of Triangular Diagrams.

Isomorphism.—One of the simplest and most effective uses of triangular diagrams is illustrated in Fig. 75, the object being to display the degree of isomorphism between

three similar compounds. The example chosen¹ shows the distribution of points representing the composition of certain garnets. *Pyrope*, represented by the molecular proportion of MgO , is placed at one corner, *almandine*, represented by the molecular proportion of FeO at another, and *spessartite*, represented by the molecular proportion of MnO at the third. The distribution of the points brings out very clearly the perfect isomorphism between pyrope and almandine, and between the latter and spessartite, and shows the almost complete absence of isomorphism between pyrope and spessartite except in the presence of abundant almandine, the common member of the two series.

Other interesting diagrams of this kind could be drawn to represent the relations between—

- (a) orthoclase, albite, and anorthite.
- (b) normative CaSiO_3 , MgSiO_3 , and FeSiO_3 in pyroxenes and amphiboles, to show the relations of particular minerals to diopside, hedenbergite, enstatite, hypersthene, enstatite-diopside, etc., or tremolite, actinolite, grünerite, etc.
- (c) magnetite, chromite, and spinel.
- (d) the rhombic carbonates, calcite, magnesite, and siderite, bringing out relations to dolomite, breunnerite and ankerite.

Other associations will occur to those engaged on particular problems.

Exogenetic Rocks.—The variation in lateritic rocks and associated deposits can be well displayed by a triangular diagram in which *quartz*, *clay*, and *lateritic constituents* are taken as the dominant variables. The numerous possibilities and the nomenclature are illustrated by Fig. 76.

Ordinary detrital sediments and limestones may be

¹ H. E. Boeke: *Grundlagen der Physikalische Chemischen Petrographie*, 1915.

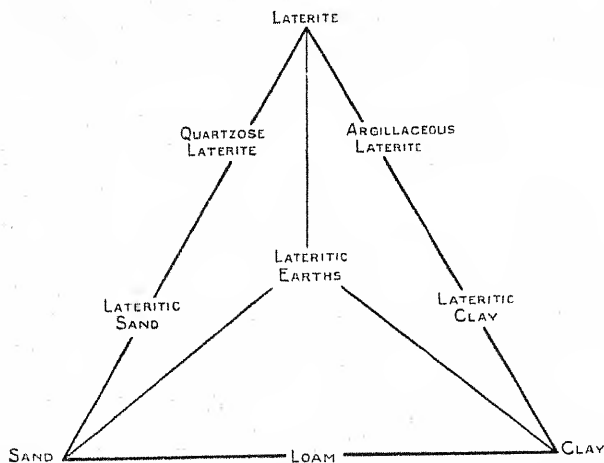


Fig. 76.—Triangular diagram to illustrate the nomenclature for describing laterite-sand-clay deposits. Cf. Fig. 49.

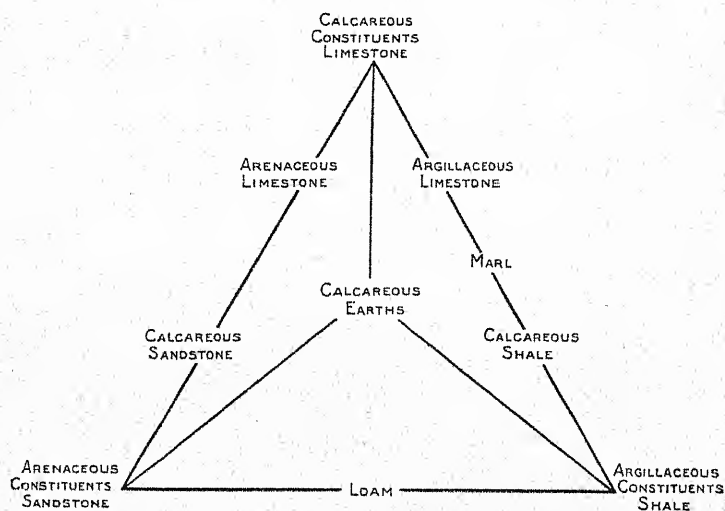


Fig. 77.—Triangular diagram to illustrate the nomenclature of calcareous sediments.

expressed by plotting points in terms of *silica* (or silica and felspar, etc., together, as the arenaceous constituents), *clay* (or clay and allied minerals in general as the argillaceous constituents), and *calcium carbonate* (or carbonate-minerals in general). See Fig. 77. The plotting of the three grades, *sand*, *silt*, and *clay*, has already been dealt with on page 227.

Igneous and Metamorphic Rocks. — In dealing with igneous rock-series it is not often that three constituents alone are sufficiently dominant to present an adequate picture of the rock-types and their relations. Variation-diagrams of the kinds already discussed are therefore generally more valuable for interpretive study than those in which trilinear co-ordinates are used. If groups of constituents are taken more significant results may be obtained. Thus the three groups of *felsic* minerals, *mafic* minerals (other than ores) and *ore*-minerals (magnetite, ilmenite, sulphides, etc.), or their normative analogues may sometimes be taken as the three variables in a rock-series. Where a rock-series is composed throughout mainly of three minerals (*e.g.*, pyroxene, olivine, and plagioclase in a series comprising peridotite, pyroxenite, troctolite and gabbro) the data are simpler and the relations likely to be more intimate. In certain volcanic rocks degree of crystallisation could be studied by plotting *phenocrysts*, *crystalline groundmass* and *glass*. Many other cases of three variables arise in particular problems, and can be graphically represented in this way.

Osann has employed trilinear co-ordinates to investigate the chemical characters of certain groups of igneous rocks, particularly with a view to distinguishing alkali- and calc-alkali rocks, and to demonstrate the outstanding differences between igneous rocks and detrital sediments.¹ Two groupings of constituents which he has adopted for these purposes are—

¹ A. Osann: *Abh. Heidelberger Akad. Wiss. Math. Nat. Kl.*, 1913, p. 163; *Sitz. ber. Heidelberger Akad. Wiss. Math. Nat. Kl.*, 1914, A. xxvi.

- (a) SiO_2 , Al_2O_3 , and $(\text{Ca}, \text{Mg}, \text{Fe})\text{O}$;
 (b) Al_2O_3 , CaO , and $(\text{Na}, \text{K})_2\text{O}$.

In a similar way Grubenmann has attempted to distinguish twelve groups of metamorphic rocks on a quantitative chemical basis.¹ His groups are as follows :—

- | | |
|--------------------------------|----------------------------|
| 1. Alkali-felspar gneisses. | 7. Chloromelanite-rocks. |
| 2. Alumino-silicate gneisses. | 8. Quartzites. |
| 3. Lime-soda-felspar gneisses. | 9. Lime-silicate-rocks. |
| 4. Eclogites and amphibolites. | 10. Marmorites. |
| 5. Magnesium silicate schists. | 11. Iron oxide-rocks. |
| 6. Jadeite-rocks. | 12. Aluminium oxide-rocks. |

Grubenmann's method of dealing with the chemical analysis is a modification of an earlier treatment adopted by Osann. With the aid of molecular proportions TiO_2 and P_2O_5 are added to SiO_2 ; Fe_2O_3 , Cr_2O_3 , MnO , NiO , and CoO are added to FeO ; BaO and SrO are added to CaO ; and H_2O is neglected. The resulting groups of molecular proportions, together with Al_2O_3 , MgO , Na_2O and K_2O , are then reduced to molecular percentages. Seven "group-values" are then calculated, thus :—

S = the modified molecular percentage of SiO_2 .

A = the sum of the molecular percentages of the Na_2O and K_2O , which are combined with Al_2O_3 in the 1 : 1 ratio.

C = the molecular percentage of the CaO combined with Al_2O_3 in the 1 : 1 ratio.

M = the molecular percentage of the CaO residual from C.

F = the sum of the molecular percentages of MgO , FeO , and M.

T = the molecular percentage of any residual Al_2O_3 from A and C.

K = the quotient
$$\frac{S}{6A + 2C + F}$$

¹ U. Grubenmann : *Die Kristallinen Schiefer*, I, 1904; II, 1907.

The "group-values" for the means of each of the twelve groups are listed below. For graphical representation three variables (projection-values) are calculated from the group-values thus—

$$a = \frac{20A}{A+C+F}; \quad c = \frac{20C}{A+C+F}; \quad f = \frac{20F}{A+C+F}.$$

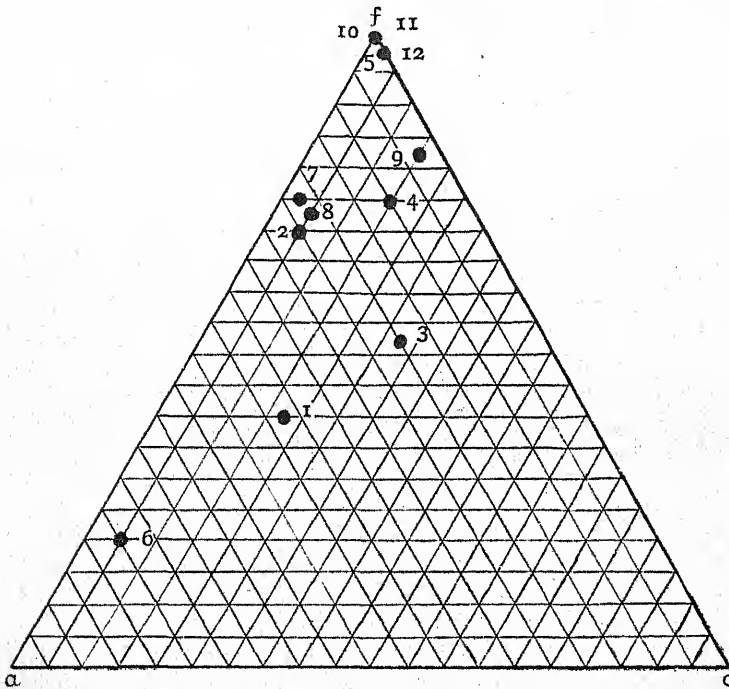


Fig. 78.—Triangular diagram representing Grubenmann's classification of metamorphic rocks.

Plotting the sets of three figures thus obtained in a triangle with sides divided into twenty parts (*Fig. 78*), one is disappointed to find that they nearly all fall into a small part of the triangle, showing that the best choice of variables to cover the whole field has not been made. Moreover, the

points for groups 10 and 11 are coincident; those for 5 and 12 are coincident; and all four are nearly coincident. Reference to these groups will show that they are widely different, and it can only be concluded that a method of graphic representation which fails to give them distinctive places also fails in its whole purpose. Metamorphic rocks, as a whole, cannot be satisfactorily referred to any three dominant chemical characters or groups of characters, and though in any individual area it may be possible, the three that should be chosen will not necessarily be those adopted by Grubenmann.

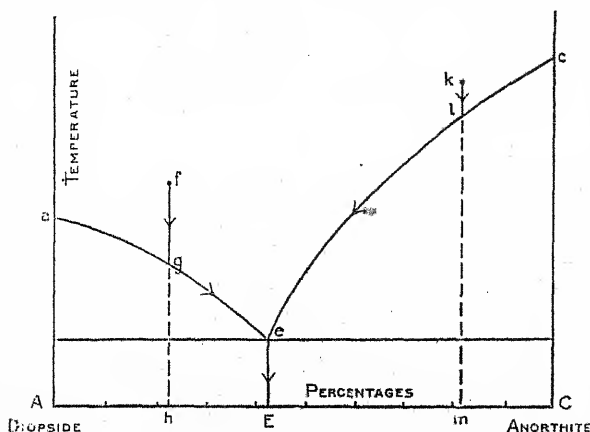
Group	Group-Values.							Projection-Values		
	S.	A.	C.	F.	M.	T.	K.	a	b	f
1	76.5	6.6	2.0	5.7	—	1.0	1.6	8.5	3.5	8.0
2	65.3	4.9	1.8	13.0	—	8.5	1.5	5.0	1.0	14.0
3	67.0	4.2	6.4	11.6	1.2	—	1.4	4.0	5.5	10.5
4	53.0	3.9	5.8	29.9	6.9	—	0.8	2.0	3.0	15.0
5	44.0	0.3	1.7	50.0	3.2	2.3	0.8	—	0.5	19.5
6	64.0	14.0	1.0	4.5	1.3	0.4	0.7	15.0	1.0	4.0
7	57.0	7.4	0.6	25.2	7.0	—	0.8	4.5	0.5	15.0
8	87.6	2.3	0.3	5.3	0.1	2.5	9.5	4.5	1.0	14.5
9	55.5	1.2	5.5	30.5	19.5	—	1.1	0.5	3.0	16.5
10	—	—	—	100.0	80.0	—	—	—	—	20.0
11	20.0	—	0.4	80.0	2.5	—	0.3	—	—	20.0
12	12.0	0.5	2.5	34.0	—	52.5	0.2	—	0.5	19.5

Crystallisation of Binary Systems.

Triangular diagrams find their most valuable application in the representation of the composition of liquids which can be regarded as solutions of three components, and particularly of the ranges of composition within which certain crystals can exist in equilibrium. The sum of the phases (solutions, crystals, etc.) which can be formed under different physical conditions (temperature, etc.) from any given component, or from any proportions of two or more components, is called a *system*. Thus, with water as the component, the possible phases are gaseous (steam), liquid (water), and solid (ice and other crystalline forms). A system in which there are two components is called a *binary*

system, and as a simple example of its diagrammatic representation we may take the case of the system *diopside-anorthite*¹ (Fig. 79).

Any proportion of these components may be represented by a point on the line AC, where C represents 100 per cent. of anorthite measured from A, and A represents 100 per cent. of diopside measured from C. Composition



. 79.—Equilibrium diagram of the eutectic system diopside-anorthite.

is thus represented by abscissæ, and temperature may be represented by ordinates. Any point in the rectangular field so determined then represents a particular composition and a particular temperature. Consider the composition indicated by the vertical line fh, where f represents a temperature at which the two components are in mutual solution. As cooling proceeds a point g will be reached at which diopside begins to crystallise. Similarly, starting from a point k, a point l will be reached at which anorthite begins to crystallise. By carrying out a suitable series of experiments the loci of all points, such as g and l, can be determined. Thus a curve a g e is traced for

¹ N. L. Bowen : *Am. Journ. Sci.*, xxxviii, 1914, p. 222.

diopside, where *a* is the melting- or freezing-point of pure diopside. Similarly, a curve *c l e* is traced for anorthite, where *c* is the melting- or freezing-point of pure anorthite. At the point *e* where these two curves intersect the two minerals crystallise together as a *eutectic mixture* in the ratio determined by

$$\frac{\text{Percentage of Anorthite}}{\text{Percentage of Diopside}} = \frac{AE}{CE}.$$

The temperature corresponding to the point *e* is called the *eutectic point*.

The cooling history of such a system may now be briefly stated :—

- | | |
|--|---|
| <p style="text-align: center;"><i>Cooling from f.</i></p> <p><i>fg.</i>—Cooling of the solution until saturation is reached at <i>g.</i></p> <p><i>ge.</i>—Crystallisation of diopside with concomitant change of composition of the solution accompanied by decreasing temperature.</p> | <p style="text-align: center;"><i>Cooling from k.</i></p> <p><i>kl.</i>—Cooling of the solution until saturation is reached at <i>l.</i></p> <p><i>le.</i>—Crystallisation of anorthite with concomitant change of composition of the solution accompanied by decreasing temperature.</p> |
|--|---|
- e.*—Crystallisation of diopside and anorthite in the eutectic ratio, and without further decrease of temperature, until the whole solution has crystallised.
- eE.*—Cooling of the crystalline aggregate of diopside and anorthite in the ordinary way.

As a further example we may consider the system *albite-anorthite*¹ (*Fig. 80*). These two constituents do not form a eutectic, but are isomorphous. As before composition is represented by abscissæ and temperature by ordinates. Starting from a point of composition and temperature represented by *p*, cooling takes place until a

¹ N. L. Bowen : *Am. Journ. Sci.*, xxxv, 1913, p. 583.

point *k* is reached when crystallisation begins. The crystals that separate in this case are, however, neither pure albite nor pure anorthite, but plagioclase having a composition *K*, where *k* and *K* lie on a horizontal line representing the same temperature throughout. As cooling proceeds, the composition of the liquid changes along the curve *k*, *l*, *m*, *n*, *b*, called the *liquidus*, while the

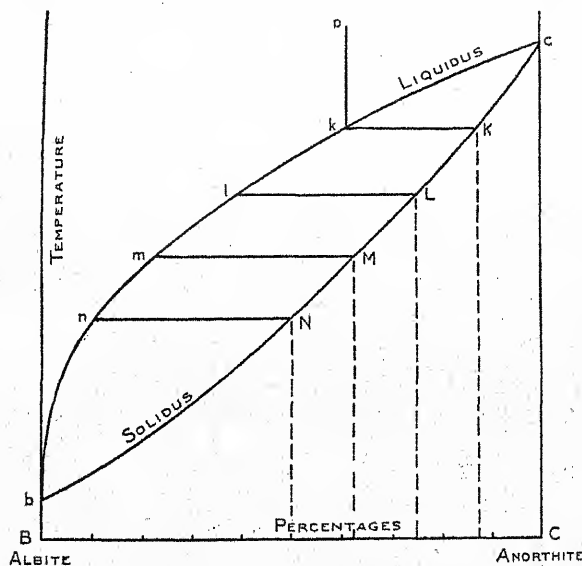


Fig. 80.—Equilibrium diagram of the isomorphous system albite-anorthite (plagioclase).

crystals forming are respectively of composition *K*, *L*, *M*, *N*, and *b*, the curve on which these points lie being called the *solidus*. Thus in the crystallisation of plagioclase the crystals are always richer in anorthite than the liquid, and the crystals themselves become steadily richer in albite as consolidation proceeds. The zoning of feldspars is the most obvious example of the operation of this process.

Crystallisation of Ternary Systems.

When it is desired to illustrate a system of three constituents the triangular diagram is adopted, since it shows the composition of every possible mixture. Each side then corresponds with a binary system. In order to represent temperatures ordinates perpendicular to the plane of the

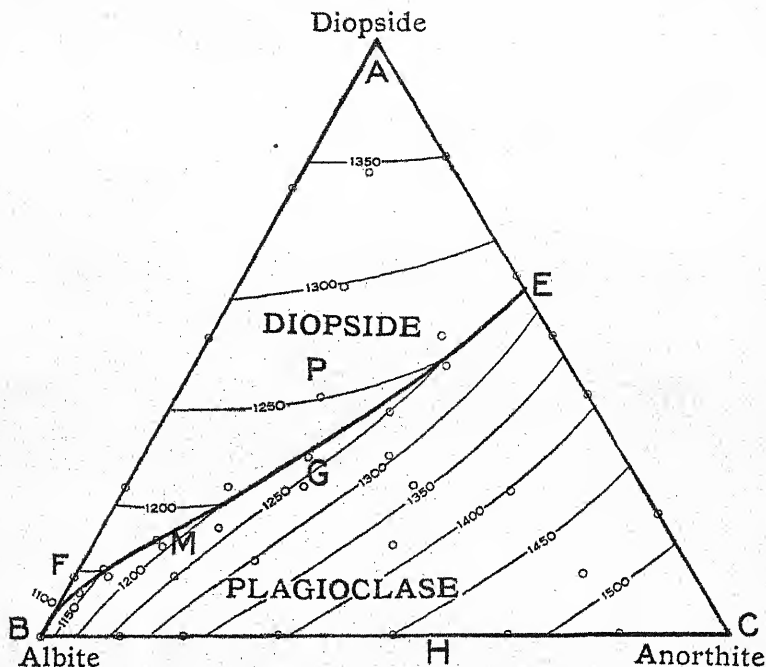


Fig. 81.—Equilibrium diagram of the ternary system diopside-albite-anorthite.

triangle must be erected, and in place of the curves representing freezing- or melting-points we now have surfaces. The most convenient way of representing the form of the surfaces is to project their contours on the triangle. Heights being here proportional to temperatures, contours become isotherms, and instead of a number of feet (as on topographic maps) the contour interval is a number of

degrees. Thus every point in the triangle now represents a definite temperature, as well as a unique composition.

The System Diopside-Plagioclase.—The equilibrium diagram of the ternary system *diopside-anorthite-albite* is illustrated in Fig. 81. The side BC corresponds to BC in Fig. 80, and the side AC corresponds to AC in Fig. 79. The remaining side AB represents the binary system *diopside-albite*. This is a eutectic system with the eutectic

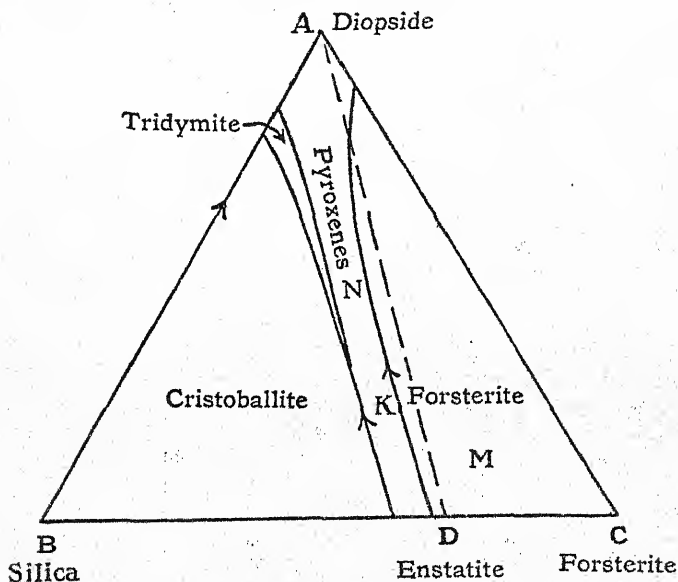


Fig. 82.—Equilibrium diagram of the ternary system diopside-forsterite-silica.

close to albite, the component of lower melting-point. The eutectic ratio is indicated by the point F, where albite is about 97 per cent., and the temperature about 1085°C . It is to be expected, therefore, that the combination of these three binaries will give a freezing-surface corresponding to hills at C and A, and a valley at E sloping down towards F, which is the lowest point. The distribution of the temperature-contours or isotherms shows this to be the case. The valley EF has for the whole system the same sort of

significance as the eutectic points E and F themselves. It represents the compositions of all solutions with which both diopside and a particular plagioclase are in equilibrium, and for each composition it indicates the temperature at which diopside and a particular plagioclase will crystallise.

On the diopside side of the valley the field AEF contains points representing all solutions from which diopside alone first begins to crystallise, and the temperature in each case at which crystallisation begins. Similarly on the plagioclase side of the valley the field BCEF contains points representing all solutions from which plagioclase alone first begins to crystallise, and again the temperature in each case at which crystallisation begins. The curve EF is called a *boundary curve*.

The cooling history of a solution of composition P may be read as follows: Cooling proceeds until the temperature-surface is reached at P. Here, at 1275°C., diopside begins to crystallise, and in consequence the composition of the liquid changes along the line APG towards G. Otherwise the ratio of albite to anorthite would be altered. When G is reached plagioclase also begins to separate but, as we have already seen, its composition is not that of the plagioclase in solution, but one richer in anorthite. Thus, instead of the composition being G¹ (where AG meets the base) it is H. The composition of the liquid then changes along the curve GMF, becoming gradually richer in albite. Both diopside and plagioclase continue to crystallise, the latter becoming richer in albite but always—until the final moment—lagging behind the liquid in this respect. This proceeds until the liquid is finally exhausted and crystallisation is complete, some point such as M having been then reached by the final drops of liquid. The actual details of the last stage of crystallisation depend on the rate of cooling which controls the amount of zoning and the consequent departure from true equilibrium.¹ When

¹ See N. L. Bowen: *The Later Stages of the Evolution of the Igneous Rocks*, *Journ. Geol.*, Supp. to xxiii, 1915, pp. 33-39.

the liquid is cooled very quickly crystallisation takes place very rapidly, if at all, and there is no time for appreciable change in the composition of the liquid. With less rapid cooling the plagioclase becomes zoned and the residual liquid is continuously enriched in albite. If the cooling be sufficiently slow the plagioclase crystals may sink, leaving the upper parts of the residual liquid still more enriched in albite. "In favourable cases the final liquid may be *more than 90 per cent. albite*, even though the original mixture were, say, 50 per cent. diopside and 50 per cent. bytownite."

The diagram also has an important bearing on order of crystallisation. If the original liquid (magma) lies in the plagioclase-field then the first material to commence crystallisation will be plagioclase. If, however, it lies in the diopside-field then that mineral will appear first.

The System Diopside-Forsterite-Silica. — Fig. 82 illustrates the system diopside-forsterite-silica.¹ Isotherms are not plotted, but the direction of falling temperature is indicated on each boundary curve by an arrow. Between B (silica) and C (forsterite) a point D represents enstatite, and the line (dotted) joining this to A is called the *conjugation-line*, and represents every possible mixture of enstatite and diopside. The triangle is divided into four fields:

- (a) a *forsterite*-field, giving the composition of all liquids with which forsterite crystals can exist in equilibrium;
- (b) a field of *pyroxenes*, varying continuously in composition from clinoenstatite to diopside;
- (c) a *tridymite*-field; and
- (d) a *cristobalite*-field.

From a point M the cooling history is as follows: When the appropriate temperature is reached crystallisation begins with forsterite, and the composition of the liquid changes in the direction CMK, until the conjuga-

¹ N. L. Bowen : *Am. Journ. Sci.*, xxxviii, 1914, p. 207.

tion-line is crossed and the first boundary curve is reached at K. When K is reached more forsterite will have separated than corresponds to the original amount represented by the point M since the conjugation-line has been crossed. The excess now begins to be redissolved and at the same time pyroxene begins to crystallise. Now, just as the plagioclase separating in the previous system is

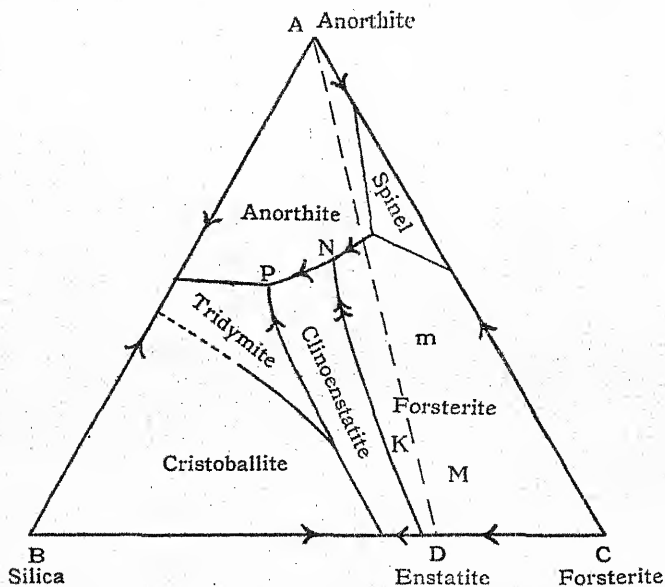


Fig. 83.—Equilibrium diagram of the ternary system anorthite-forsterite-silica.

richer in anorthite than the liquid, so here the pyroxene is richer in clinoenstatite than the liquid. The composition of the liquid thus becomes enriched in diopside, and finally a position such as N is reached when the liquid is finally exhausted. At this point the mineral aggregate consists of clinoenstatite-diopside (which may be zoned) and forsterite (showing resorbed borders).

*The System Anorthite-Forsterite-Silica.*¹—The equilibrium diagram for this system is illustrated by *Fig. 83*. It will be noticed that the lower part of the diagram resembles *Fig. 82*, but with clinoenstatite as the pyroxene instead of a series of clinoenstatite-diopside mix-crystals. In place of diopside, however, two fields representing anorthite and spinel appear in the upper part of the triangle. From a point M crystallisation of forsterite proceeds as before until the conjugation-line is crossed and the first boundary curve is reached at K. Here, also as before, forsterite begins to be redissolved, and clinoenstatite separates, and the composition of the liquid changes along the boundary curve till the point N is reached. Here anorthite also begins to separate until the liquid is exhausted. The mineral aggregate then consists of forsterite, clinoenstatite, and anorthite.

If crystallisation started from a point m to the right of the line joining C and N, then forsterite again is the first to crystallise, but at the point N it will all be redissolved, and a certain amount of liquid will still remain. Cooling will then proceed along the anorthite-clinoenstatite boundary-curve with continued crystallisation of the two minerals until P is reached. Here tridymite also begins to separate until the liquid is exhausted. The mineral aggregate then consists of clinoenstatite, anorthite, and tridymite.

Such cooling histories may be greatly modified by rate of cooling and sinking of crystals, and for an authoritative account of the various possibilities and their bearing on petrology the reader is referred to Bowen's *Later Stages of the Evolution of the Igneous Rocks*.²

¹ O. Anderson : *Am. Journ. Sci.*, xxxix, 1915, p. 407.

² *Journ. Geol.*, Supp. to xxiii, 1915.

APPENDIX A.

Numerical Data and Factors.

LENGTH.

1 micromillimetre or $1 \mu\mu = \frac{1}{1,000} \mu = \frac{1}{1,000,000} \text{ mm.}$

1 micron or $1 \mu = 1,000 \mu\mu = \frac{1}{1,000} \text{ mm.}$

NOTE.—A good thin section should have a thickness of 20-40 μ .
The pores of ordinary filter paper have a diameter of 3-4 μ .

The wave lengths of light of different colours range from 400 $\mu\mu$ (violet) to 770 $\mu\mu$ (red).

Colloidal particles range in diameter from 1-100 $\mu\mu$, and typical molecules have diameters of from 0.1 to 1 $\mu\mu$.

CONVERSION EQUIVALENTS.

1 inch	=	25.4	mms.	1 mm.	=	0.0394	inch
1 foot	=	30.48	cms.	1 cm.	=	0.0328	foot
1 foot	=	0.3048	m.	1 metre	=	3.28	feet
				1 metre	=	39.37	inches
1 yard	=	0.9144	m.	1 metre	=	1.09	yards
1 mile	=	1609.3	m.	1 km.	=	1093.6	yards
1 mile	=	1.61	km.	1 km.	=	0.62	mile

MENSURATION.

Circumference of a circle, radius $r = 2\pi r$.

Circumference of an ellipse, semi-axes a and $b = 2\pi \sqrt{\frac{a^2 + b^2}{2}}$

Mean radius of the earth = $6.371 \times 10^8 \text{ cms.}$

AREA.

CONVERSION EQUIVALENTS.

1 sq. inch	=	6.451	sq. cms.	1 sq. cm.	=	0.155	sq. inch
1 sq. foot	=	0.093	sq. m.	1 sq. metre	=	10.674	sq. feet
1 sq. yard	=	0.336	sq. m.	1 sq. metre	=	1.19	sq. yards
1 sq. mile	=	2.5898	sq. km.	1 sq. km.	=	0.386	sq. mile

MENSURATION.

Area of a circle, radius $r = \pi r^2$

Area of an ellipse, semi-axes a and $b = \pi ab$.

Area of a sphere, radius $r = 4\pi r^2$

Area of the earth = $51.18 \times 10^{17} \text{ sq. cms.}$

Area of land = $14.46 \times 10^{17} \text{ sq. cms.}$

Area of sea = $36.72 \times 10^{17} \text{ sq. cms.}$

VOLUME.

CONVERSION EQUIVALENTS.

1 cu. inch = 16.387 ccs.	1 cc. = 0.061 cu. inch	
1 cu. foot = 1728 cu. ins.	1 cu. metre = 35.317 cu. feet	
= 0.028 cu. m.	= 1.31 cu. yards	
1 pint = 0.568 litre	1 litre } = { 1.76 pints	
1 gallon = 4.546 litres	1,000 ccs. } = { 0.22 gallon	
		61.02 cu. ins.

MENSURATION.

Volume of a sphere, radius $r = \frac{4}{3}\pi r^3$

Volume of a cylinder, height $h = \pi r^2 h$

Volume of a cone, height $h = \frac{1}{3}\pi r^2 h$

Volume of earth = 1.083×10^{27} ccs.

Volume of oceans = 1.414×10^{24} ccs.

MASS AND WEIGHT.

CONVERSION EQUIVALENTS.

1 grain = 64.8 mgrms.	1 mgrm. = 0.0154 grain
= 0.065 grm.	1 gram = 15.43 grains
1 ounce = 437.5 grains	
= 28.35 grms.	1 gram = 0.035 ounce
1 lb. = 7000 grains	
= 453.6 grms.	
= 0.45 kgm.	1 kilogram = 2.20 lbs.

1 metric carat = 0.2 gram.

1 long ton = 2240 lbs. = 1016 kilograms

1 metric ton = 2205 lbs. = 1000 kilograms

1 short ton = 2000 lbs. = 907 kilograms

1 gallon of water weighs 10 lbs.

1 cubic foot of water weighs 62.425 lbs. = 1000 ozs. (approx.).

1 cubic foot of a substance having a specific gravity

S.G. weighs $62.425 \times \text{S.G.} = \frac{1,000 \text{ S.G.}}{16}$ lbs.

Mass of the earth = 5.987×10^{27} grams.

Mean density of the earth = 5.527

Mass of the oceans = 1.452×10^{21} grams.

Mean density of the oceans = 1.027

TEMPERATURE.

Conversion from degrees Centigrade, C.°, to degrees Fahrenheit, F.°—

$$\text{C.}^\circ = \frac{5}{9} (\text{F.}^\circ - 32^\circ)$$

$$\text{F.}^\circ = \frac{9\text{C.}^\circ}{5} + 32^\circ$$

SCALE OF HARDNESS.

1 Talc	6 Felspar
2 Gypsum or Rock salt	7 Quartz
3 Calcite	8 Topaz
4 Fluorite	9 Corundum
5 Apatite	10 Diamond

International Atomic Weights (1920)

O = 16.		O = 16.	
Aluminium	Al 27.1	Neodymium.....	Nd 144.3
Antimony	Sb 120.2	Neon.....	Ne 20.2
Argon	A 39.9	Nickel	Ni 58.68
Arsenic	As 74.96	Niton (Ra-eman-	
Barium	Ba 137.37	tion).....	Nt 222.0
Bismuth	Bi 208.0	Nitrogen	N 14.01
Boron	B 10.9	Osmium	Os 190.9
Bromine	Br 79.92	Oxygen	O 16.00
Cadmium	Cd 112.40	Palladium	Pd 106.7
Cæsium	Cs 132.81	Phosphorus	P 31.04
Calcium	Ca 40.07	Platinum	Pt 195.2
Carbon	C 12.00	Potassium.....	K 39.10
Cerium	Ce 140.25	Praseodymium ...	Pr 140.9
Chlorine.....	Cl 35.46	Radium	Ra 226.0
Chromium	Cr 52.0	Rhodium	Rh 102.9
Cobalt.....	Co 58.97	Rubidium	Rb 85.45
Columbium	Cb 93.1	Ruthenium	Ru 101.7
Copper	Cu 63.57	Samarium	Sa 150.4
Dysprosium	Dy 162.5	Scandium.....	Sc 44.1
Erbium	Er 167.7	Selenium	Se 79.2
Europium	Eu 152.0	Silicon	Si 28.3
Fluorine.....	F 19.0	Silver	Ag 107.88
Gadolinium	Gd 157.3	Sodium.....	Na 23.00
Gallium	Ga 70.1	Strontium	Sr 87.63
Germanium	Ge 72.5	Sulphur	S 32.06
Glucinum	Gl 9.1	Tantalum.....	Ta 181.5
Gold	Au 197.2	Tellurium	Te 127.5
Helium	He 4.00	Terbium	Tb 159.2
Holmium	Ho 163.5	Thallium	Tl 204.0
Hydrogen	H 1.008	Thorium	Th 232.15
Indium	In 114.8	Thulium	Tm 168.5
Iodine.....	I 126.92	Tin	Sn 118.7
Iridium	Ir 193.1	Titanium	Ti 48.1
Iron.....	Fe 55.84	Tungsten	W 184.0
Krypton	Kr 82.92	Uranium	U 238.2
Lanthanum	La 139.0	Vanadium	V 51.0
Lead	Pb 207.20	Xenon	Xe 130.2
Lithium	Li 6.94	Ytterbium (Neo-	
Lutecium	Lu 175.0	ytterbium)	Yb 173.5
Magnesium	Mg 24.32	Yttrium	Yt 89.38
Manganese.....	Mn 54.93	Zinc	Zn 65.37
Mercury	Hg 200.6	Zirconium	Zr 90.6
Molybdenum.....	Mo 96.0		

APPENDIX B.

Molecular Proportions.

SiO_2

SILICA

60

(Divide percentage weight by 60.)

Al_2O_3

ALUMINA

102

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
1	.010	.011	.012	.013	.014	.015	.016	.017	.018	.019
2	.020	.021	.022	.023	.024	.025	.026	.027	.028	.029
3	.030	.031	.032	.033	.034	.035	.036	.037	.038	.039
4	.040	.041	.042	.043	.044	.045	.046	.047	.048	.049
5	.050	.051	.052	.053	.054	.055	.056	.057	.058	.059
6	.060	.061	.062	.063	.064	.065	.066	.067	.068	.069
7	.070	.071	.072	.073	.074	.075	.076	.077	.078	.079
8	.080	.081	.082	.083	.084	.085	.086	.087	.088	.089
9	.090	.091	.092	.093	.094	.095	.096	.097	.098	.099
10	.100	.101	.102	.103	.104	.105	.106	.107	.108	.109
11	.110	.111	.112	.113	.114	.115	.116	.117	.118	.119
12	.120	.121	.122	.123	.124	.125	.126	.127	.128	.129
13	.130	.131	.132	.133	.134	.135	.136	.137	.138	.139
14	.140	.141	.142	.143	.144	.145	.146	.147	.148	.149
15	.150	.151	.152	.153	.154	.155	.156	.157	.158	.159
16	.160	.161	.162	.163	.164	.165	.166	.167	.168	.169
17	.170	.171	.172	.173	.174	.175	.176	.177	.178	.179
18	.180	.181	.182	.183	.184	.185	.186	.187	.188	.189
19	.190	.191	.192	.193	.194	.195	.196	.197	.198	.199
20	.200	.201	.202	.203	.204	.205				

Fe_2O_3

FERRIC OXIDE

160

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
1	.010	.011	.012	.013	.014	.015	.016	.017	.018	.019
2	.020	.021	.022	.023	.024	.025	.026	.027	.028	.029
3	.030	.031	.032	.033	.034	.035	.036	.037	.038	.039
4	.040	.041	.042	.043	.044	.045	.046	.047	.048	.049
5	.050	.051	.052	.053	.054	.055	.056	.057	.058	.059
6	.060	.061	.062	.063	.064	.065	.066	.067	.068	.069
7	.070	.071	.072	.073	.074	.075	.076	.077	.078	.079
8	.080	.081	.082	.083	.084	.085	.086	.087	.088	.089
9	.090	.091	.092	.093	.094	.095	.096	.097	.098	.099
10	.100	.101	.102	.103	.104	.105	.106	.107	.108	.109

FeO

FERROUS OXIDE

72

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.003	.004	.006	.007	.008	.010	.011	.013
1	.014	.015	.017	.018	.019	.021	.022	.024	.025	.026
2	.028	.029	.031	.032	.033	.035	.036	.038	.039	.040
3	.042	.043	.044	.046	.047	.049	.050	.051	.053	.054
4	.056	.057	.058	.060	.061	.063	.064	.065	.067	.068
5	.069	.071	.072	.074	.075	.076	.078	.079	.081	.082
6	.083	.085	.086	.088	.089	.090	.092	.093	.094	.096
7	.097	.099	.100	.101	.103	.104	.106	.107	.108	.110
8	.111	.113	.114	.115	.117	.118	.119	.121	.122	.124
9	.125	.126	.128	.129	.131	.132	.133	.135	.136	.138
10	.139	.140	.142	.143	.144	.146	.147	.149	.150	.151

MgO

MAGNESIA

40

(Divide percentage weight by 40.)

CaO

LIME

56

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.002	.004	.005	.007	.009	.011	.013	.014	.016
1	.018	.020	.021	.023	.025	.027	.029	.030	.032	.034
2	.036	.038	.039	.041	.043	.045	.046	.048	.050	.052
3	.054	.055	.057	.059	.061	.063	.064	.066	.068	.070
4	.071	.073	.075	.077	.079	.080	.082	.084	.086	.088
5	.089	.091	.093	.095	.096	.098	.100	.102	.104	.105
6	.107	.109	.111	.113	.114	.116	.118	.120	.121	.123
7	.125	.127	.129	.130	.132	.134	.136	.138	.139	.141
8	.143	.145	.146	.148	.150	.152	.154	.155	.157	.159
9	.161	.163	.164	.166	.168	.170	.171	.173	.175	.177
10	.179	.180	.182	.184	.186	.188	.189	.191	.193	.195

Na₂O

SODA

62

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.002	.003	.005	.006	.008	.010	.011	.013	.015
1	.016	.018	.019	.021	.023	.024	.026	.027	.029	.031
2	.032	.034	.035	.037	.039	.040	.042	.044	.045	.047
3	.048	.050	.052	.053	.055	.056	.058	.060	.061	.063
4	.065	.066	.068	.069	.071	.073	.074	.076	.077	.079
5	.081	.082	.084	.085	.087	.089	.090	.092	.094	.095
6	.097	.098	.100	.102	.103	.105	.106	.108	.110	.111
7	.113	.115	.116	.118	.119	.121	.123	.124	.126	.127
8	.129	.131	.132	.134	.135	.137	.139	.140	.142	.144
9	.145	.147	.148	.150	.152	.153	.155	.156	.158	.160
10	.161	.163	.165	.166	.168	.169	.171	.173	.174	.176

APPENDIX B

497

 K_2O

POTASH

94

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.002	.003	.004	.005	.006	.007	.009	.010
1	.011	.012	.015	.014	.015	.016	.017	.018	.019	.020
2	.021	.022	.023	.024	.026	.027	.028	.029	.030	.031
3	.032	.033	.034	.035	.036	.037	.038	.039	.040	.041
4	.043	.044	.045	.046	.047	.048	.049	.050	.051	.052
5	.053	.054	.055	.056	.057	.059	.060	.061	.062	.063
6	.064	.065	.066	.067	.068	.069	.070	.071	.072	.073
7	.074	.076	.077	.078	.079	.080	.081	.082	.083	.084
8	.085	.086	.087	.088	.089	.090	.091	.093	.094	.095
9	.096	.097	.098	.099	.100	.101	.102	.103	.104	.105
10	.106	.107	.109	.110	.111	.112	.113	.114	.115	.116

 H_2O

WATER

18

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.006	.011	.017	.022	.028	.033	.039	.044	.050
1	.056	.061	.067	.072	.078	.083	.089	.094	.100	.106
2	.111	.117	.122	.128	.133	.139	.144	.150	.156	.161
3	.167	.172	.178	.183	.189	.194	.200	.206	.211	.217
4	.222	.228	.233	.239	.244	.250	.256	.261	.267	.272
5	.278	.283	.289	.294	.300	.306	.311	.317	.322	.328

 CO_2

CARBON DIOXIDE

44

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.002	.005	.007	.009	.011	.014	.016	.018	.020
1	.023	.025	.027	.030	.032	.034	.036	.039	.041	.043
2	.045	.048	.050	.052	.055	.057	.059	.061	.064	.066
3	.068	.070	.073	.075	.077	.080	.082	.084	.086	.089
4	.091	.093	.095	.098	.100	.102	.105	.107	.109	.111
5	.114	.116	.118	.120	.123	.125	.127	.130	.132	.134

 TiO_2

TITANIUM DIOXIDE

80

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.003	.004	.005	.006	.008	.009	.010	.011
1	.013	.014	.015	.016	.018	.019	.020	.021	.023	.024
2	.025	.026	.028	.029	.030	.031	.033	.034	.035	.036
3	.038	.039	.040	.041	.043	.044	.045	.046	.048	.049
4	.050	.051	.053	.054	.055	.056	.058	.059	.060	.061
5	.063	.064	.065	.066	.068	.069	.070	.07	.073	.074

P_2O_5

PHOSPHORIC PENTOXIDE

142

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.001	.002	.003	.004	.004	.005	.006	.006
1	.007	.008	.008	.009	.010	.011	.011	.012	.013	.013
2	.014	.015	.015	.016	.017	.018	.018	.019	.020	.020
3	.021	.022	.023	.023	.024	.025	.025	.026	.027	.027
4	.028	.029	.030	.030	.031	.032	.032	.033	.034	.035
5	.035	.036	.037	.037	.038	.039	.039	.040	.041	.042

MnO

MANGANOUS OXIDE

71

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.003	.004	.006	.007	.008	.010	.011	.013
1	.014	.015	.017	.018	.020	.021	.023	.024	.025	.027
2	.028	.030	.031	.032	.034	.035	.037	.038	.039	.041
3	.042	.044	.045	.046	.048	.049	.051	.052	.054	.055

ZrO₂

ZIRCONIA

123

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.002	.002	.003	.004	.005	.006	.007	.007
1	.008	.009	.010	.011	.011	.012	.013	.014	.015	.015
2	.016	.017	.018	.019	.020	.020	.021	.022	.023	.024
3	.024	.025	.026	.027	.028	.028	.029	.030	.031	.032

SO₃

SULPHUR TRIOXIDE

80

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.003	.004	.005	.006	.008	.009	.010	.011
1	.013	.014	.015	.016	.018	.019	.020	.021	.023	.024
2	.025	.026	.028	.029	.030	.031	.033	.034	.035	.036
3	.038	.039	.040	.041	.043	.044	.045	.046	.048	.049

S

SULPHUR

32

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.003	.006	.009	.013	.016	.019	.022	.025	.028
1	.031	.034	.038	.041	.044	.047	.050	.053	.056	.059
2	.063	.066	.069	.072	.075	.078	.081	.084	.088	.091
3	.094	.097	.100	.103	.106	.109	.113	.116	.119	.122

Cl₂

CHLORINE

71

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.003	.004	.006	.007	.008	.010	.011	.013
1	.014	.015	.017	.018	.020	.021	.023	.024	.025	.027
2	.028	.030	.031	.032	.034	.035	.037	.038	.039	.041
3	.042	.044	.045	.046	.048	.049	.051	.052	.054	.055

APPENDIX B

499

F₂

FLUORINE

38

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.003	.005	.008	.010	.013	.016	.018	.021	.024
1	.026	.029	.031	.034	.037	.039	.042	.045	.047	.050

Cr₂O₃

CHROMIC OXIDE

152

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.001	.002	.003	.003	.004	.005	.005	.006
1	.007	.007	.008	.009	.009	.010	.011	.011	.012	.013

NiO

NICKEL OXIDE

75

CoO

COBALT OXIDE

75

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.003	.004	.005	.007	.008	.009	.011	.012
1	.013	.015	.016	.017	.019	.020	.021	.023	.024	.025

BaO

BARYTA

153.5

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.001	.002	.003	.003	.004	.005	.005	.006
1	.007	.007	.008	.009	.009	.010	.010	.011	.012	.012

SrO

STRONTIA

103.5

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
1	.010	.011	.012	.013	.014	.014	.015	.016	.017	.018

Li₂O

LITHIA

30

%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	.000	.003	.007	.010	.013	.017	.020	.023	.027	.030
1	.033	.037	.040	.043	.047	.050	.053	.057	.060	.063

Percentage Weights for Molecular Proportions of the Normative Minerals.

 SiO_2

QUARTZ

60

(Multiply the molecular proportion of SiO_2 by 60.) $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$

ORTHOCLASE

556

(Unit of calculation is the molecular proportion of K_2O .)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.56	1.11	1.67	2.22	2.78	3.34	3.89	4.45	5.00
.01	5.56	6.12	6.67	7.23	7.78	8.34	8.90	9.45	10.01	10.56
.02	11.12	11.68	12.23	12.79	13.34	13.90	14.46	15.01	15.57	16.12
.03	16.68	17.24	17.79	18.35	18.90	19.46	20.02	20.57	21.13	21.68
.04	22.24	22.80	23.35	23.91	24.46	25.02	25.58	26.13	26.69	27.24
.05	27.80	28.36	28.91	29.47	30.02	30.58	31.14	31.69	32.25	32.80
.06	33.36	33.92	34.47	35.03	35.58	36.14	36.70	37.25	37.81	38.36
.07	38.92	39.48	40.03	40.59	41.14	41.70	42.26	42.81	43.37	43.92
.08	44.48	45.04	45.59	46.15	46.70	47.26	47.82	48.37	48.93	49.48
.09	50.04	50.60	51.15	51.71	52.26	52.82	53.38	53.93	54.49	55.04
.10	55.60	56.16	56.71	57.27	57.82	58.38	58.94	59.49	60.05	60.60

 $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$

ALBITE

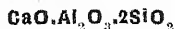
524

(Unit of calculation is the molecular proportion of Na_2O .)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.52	1.05	1.57	2.10	2.62	3.14	3.67	4.19	4.72
.01	5.24	5.76	6.29	6.81	7.34	7.86	8.38	8.91	9.43	9.96
.02	10.48	11.00	11.53	12.05	12.58	13.10	13.62	14.15	14.67	15.20
.03	15.72	16.24	16.77	17.29	17.82	18.34	18.86	19.39	19.91	20.44
.04	20.96	21.48	22.01	22.53	23.06	23.58	24.10	24.63	25.15	25.68
.05	26.20	26.72	27.25	27.77	28.30	28.82	29.34	29.87	30.39	30.92
.06	31.44	31.96	32.49	33.01	33.54	34.06	34.58	35.11	35.63	36.15
.07	36.68	37.20	37.73	38.25	38.77	39.30	39.82	40.35	40.87	41.39
.08	41.92	42.44	42.97	43.49	44.01	44.54	45.06	45.59	46.11	46.63
.09	47.16	47.68	48.21	48.73	49.25	49.78	50.30	50.83	51.35	51.87
.10	52.40	52.92	53.45	53.97	54.49	55.02	55.54	56.07	56.59	57.11

APPENDIX B.

501

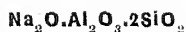


ANORTHITE

278

(Unit of calculation is the molecular proportion of CaO.)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.28	0.56	0.83	1.11	1.39	1.67	1.95	2.22	2.50
.01	2.78	3.06	3.34	3.61	3.89	4.17	4.45	4.73	5.00	5.28
.02	5.56	5.84	6.12	6.39	6.67	6.95	7.23	7.51	7.78	8.06
.03	8.34	8.62	8.90	9.17	9.45	9.73	10.01	10.29	10.56	10.84
.04	11.12	11.40	11.68	11.95	12.23	12.51	12.79	13.07	13.34	13.62
.05	13.90	14.18	14.46	14.73	15.01	15.29	15.57	15.85	16.12	16.40
.06	16.68	16.96	17.24	17.51	17.79	18.07	18.35	18.63	18.90	19.18
.07	19.46	19.74	20.02	20.29	20.57	20.85	21.13	21.41	21.68	21.96
.08	22.24	22.52	22.80	23.07	23.35	23.63	23.91	24.19	24.46	24.74
.09	25.02	25.30	25.58	25.85	26.13	26.41	26.69	26.97	27.24	27.52
.10	27.80	28.08	28.36	28.63	28.91	29.19	29.47	29.75	30.02	30.30

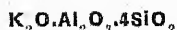


NEPHELINE

284

(Unit of calculation is the molecular proportion of Na₂O.)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.28	0.57	0.85	1.14	1.42	1.70	1.99	2.27	2.56
.01	2.84	3.12	3.41	3.69	3.98	4.26	4.54	4.83	5.11	5.40
.02	5.68	5.96	6.25	6.53	6.82	7.10	7.38	7.67	7.95	8.24
.03	8.52	8.80	9.09	9.37	9.66	9.94	10.22	10.51	10.79	11.08
.04	11.36	11.64	11.93	12.21	12.50	12.78	13.06	13.35	13.63	13.92
.05	14.20	14.48	14.77	15.05	15.34	15.62	15.90	16.19	16.47	16.76
.06	17.04	17.32	17.61	17.89	18.18	18.46	18.74	19.03	19.31	19.60
.07	19.88	20.16	20.45	20.73	21.02	21.30	21.58	21.87	22.15	22.44
.08	22.72	23.00	23.28	23.57	23.86	24.14	24.42	24.71	24.99	25.28
.09	25.56	25.84	26.13	26.41	26.70	26.98	27.26	27.55	27.83	28.12
.10	28.40	28.68	28.97	29.25	29.54	29.82	30.10	30.39	30.67	30.96



LEUCITE

436

(Unit of calculation is the molecular proportion of K₂O.)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.44	0.87	1.31	1.74	2.18	2.62	3.05	3.49	3.92
.01	4.36	4.80	5.23	5.67	6.10	6.54	6.98	7.41	7.85	8.28
.02	8.72	9.16	9.59	10.03	10.46	10.90	11.34	11.77	12.21	12.64
.03	13.08	13.52	13.95	14.39	14.82	15.26	15.70	16.13	16.57	17.00
.04	17.44	17.88	18.31	18.75	19.18	19.62	20.06	20.49	20.93	21.36
.05	21.80	22.24	22.67	23.11	23.54	23.98	24.42	24.85	25.29	25.72
.06	26.16	26.60	27.03	27.47	27.90	28.34	28.78	29.21	29.65	30.08
.07	30.52	30.96	31.39	31.83	32.26	32.70	33.14	33.57	34.01	34.44
.08	34.88	35.32	35.75	36.19	36.62	37.06	37.50	37.93	38.37	38.80
.09	39.24	39.68	40.11	40.55	40.98	41.42	41.86	42.29	42.73	43.16
.10	43.60	44.04	44.47	44.91	45.34	45.78	46.22	46.65	47.09	47.52

CALCIUM METASILICATE
CaO.SiO₂ (WOLLASTONITE) 116
(Unit of calculation is the molecular proportion of CaO.)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.12	0.23	0.35	0.46	0.58	0.70	0.81	0.93	1.04
.01	1.16	1.28	1.39	1.51	1.63	1.74	1.86	1.97	2.09	2.20
.02	2.32	2.44	2.55	2.67	2.78	2.90	3.02	3.13	3.25	3.36
.03	3.48	3.60	3.71	3.83	3.94	4.06	4.18	4.29	4.41	4.52
.04	4.64	4.76	4.87	4.99	5.10	5.22	5.34	5.45	5.57	5.68
.05	5.80	5.92	6.03	6.15	6.26	6.38	6.50	6.61	6.73	6.84
.06	6.96	7.08	7.19	7.31	7.42	7.54	7.66	7.77	7.89	8.00
.07	8.12	8.24	8.35	8.47	8.58	8.70	8.82	8.93	9.05	9.16
.08	9.28	9.40	9.51	9.63	9.74	9.86	9.98	10.09	10.21	10.32
.09	10.44	10.56	10.67	10.79	10.90	11.02	11.14	11.25	11.37	11.4
.10	11.60	11.72	11.83	11.95	12.06	12.18	12.30	12.41	12.53	12.6

MAGNESIUM METASILICATE
MgO.SiO₂ (ENSTATITE) 100
(Multiply molecular proportion of MgO by 100.)

IRON METASILICATE 132
(Unit of calculation is the molecular proportion of FeO.)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.13	0.26	0.40	0.53	0.66	0.79	0.92	1.06	1.19
.01	1.32	1.45	1.58	1.72	1.85	1.98	2.11	2.24	2.38	2.51
.02	2.64	2.77	2.90	3.04	3.17	3.30	3.43	3.56	3.70	3.83
.03	3.96	4.09	4.22	4.36	4.49	4.62	4.75	4.88	5.02	5.15
.04	5.28	5.41	5.54	5.68	5.81	5.94	6.07	6.20	6.34	6.47
.05	6.60	6.73	6.86	7.00	7.13	7.26	7.39	7.52	7.66	7.79
.06	7.92	8.05	8.18	8.32	8.45	8.58	8.71	8.84	8.98	9.11
.07	9.24	9.37	9.50	9.64	9.77	9.90	10.03	10.16	10.30	10.43
.08	10.56	10.69	10.82	10.96	11.09	11.22	11.35	11.48	11.62	11.75
.09	11.88	12.01	12.14	12.28	12.41	12.54	12.67	12.80	12.94	13.07
.10	13.20	13.33	13.46	13.60	13.73	13.86	13.99	14.12	14.26	14.39

MAGNESIUM ORTHOSILICATE
2MgO.SiO₂ (FORSTERITE) 140
(Unit of calculation is one-half of the molecular proportion of MgO.)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.14	0.28	0.42	0.56	0.70	0.84	0.98	1.12	1.26
.01	1.40	1.54	1.68	1.82	1.96	2.10	2.24	2.38	2.52	2.66
.02	2.80	2.94	3.08	3.22	3.36	3.50	3.64	3.78	3.92	4.06
.03	4.20	4.34	4.48	4.62	4.76	4.90	5.04	5.18	5.32	5.46
.04	5.60	5.74	5.88	6.02	6.16	6.30	6.44	6.58	6.72	6.86
.05	7.00	7.14	7.28	7.42	7.56	7.70	7.84	7.98	8.12	8.26
.06	8.40	8.54	8.68	8.82	8.96	9.10	9.24	9.38	9.52	9.66
.07	9.80	9.94	10.08	10.22	10.36	10.50	10.64	10.78	10.92	11.06
.08	11.20	11.34	11.48	11.62	11.76	11.90	12.04	12.18	12.32	12.46
.09	12.60	12.74	12.88	13.02	13.16	13.30	13.44	13.58	13.72	13.86
.10	14.00	14.14	14.28	14.42	14.56	14.70	14.84	14.98	15.12	15.26

APPENDIX B

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2FeO.SiO₂ IRON ORTHOSILICATE (FAYALITE) 204*(Unit of calculation is one-half of the molecular proportion of FeO.)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.20	0.41	0.61	0.82	1.02	1.22	1.43	1.63	1.84
.01	2.04	2.24	2.45	2.65	2.85	3.05	3.26	3.47	3.67	3.88
.02	4.08	4.28	4.49	4.69	4.90	5.10	5.30	5.51	5.71	5.92
.03	6.12	6.32	6.53	6.73	6.94	7.14	7.34	7.55	7.75	7.96
.04	8.16	8.36	8.57	8.77	8.98	9.18	9.38	9.59	9.79	10.00
.05	10.20	10.40	10.61	10.81	11.02	11.22	11.42	11.63	11.83	12.04

2CaO.SiO₂ CALCIUM ORTHOSILICATE 172*(Unit of calculation is one-half of the molecular proportion of CaO.)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.17	0.34	0.52	0.69	0.86	1.03	1.20	1.38	1.55
.01	1.72	1.89	2.06	2.24	2.41	2.58	2.75	2.92	3.10	3.27
.02	3.44	3.61	3.78	3.96	4.13	4.30	4.47	4.64	4.82	4.99
.03	5.16	5.33	5.50	5.66	5.85	6.02	6.19	6.36	6.54	6.71
.04	6.88	7.05	7.22	7.40	7.57	7.74	7.91	8.08	8.25	8.43
.05	8.00	8.77	8.94	9.12	9.29	9.46	9.63	9.80	9.98	10.15

Na₂O.Fe₂O₃.4SiO₂ ACMITE 462*(Unit of calculation is the molecular proportion of Na₂O.)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.46	0.92	1.39	1.85	2.31	2.77	3.23	3.70	4.16
.01	4.62	5.08	5.54	6.01	6.47	6.93	7.39	7.85	8.32	8.78
.02	9.24	9.70	10.16	10.63	11.09	11.55	12.01	12.47	12.94	13.40
.03	13.86	14.32	14.78	15.25	15.71	16.17	16.63	17.09	17.56	18.02
.04	18.48	18.94	19.40	19.87	20.33	20.79	21.25	21.71	22.18	22.64
.05	23.10	23.56	24.02	24.49	24.95	25.41	25.87	26.33	26.80	27.26

Al₂O₃ CORUNDUM 102*(Unit of calculation is the molecular proportion of Al₂O₃.)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.10	0.20	0.31	0.41	0.51	0.61	0.71	0.82	0.92
.01	1.02	1.12	1.22	1.33	1.43	1.53	1.63	1.73	1.84	1.94
.02	2.04	2.14	2.24	2.35	2.45	2.55	2.65	2.75	2.86	2.96
.03	3.06	3.16	3.26	3.37	3.47	3.57	3.67	3.77	3.88	3.98
.04	4.08	4.18	4.28	4.39	4.49	4.59	4.69	4.79	4.90	5.00
.05	5.10	5.20	5.30	5.41	5.51	5.61	5.71	5.81	5.92	6.02

FeO.TiO₂**ILMENITE****152***(Unit of calculation is the molecular proportion of FeO.)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.15	0.30	0.46	0.61	0.76	0.91	1.06	1.22	1.37
.01	1.52	1.67	1.82	1.98	2.13	2.28	2.43	2.58	2.74	2.89
.02	3.04	3.19	3.34	3.50	3.65	3.80	3.95	4.10	4.26	4.41
.03	4.56	4.71	4.86	5.02	5.17	5.32	5.47	5.62	5.78	5.93
.04	6.08	6.23	6.38	6.54	6.69	6.84	6.99	7.14	7.30	7.45
.05	7.60	7.75	7.90	8.06	8.21	8.36	8.51	8.66	8.82	8.97

FeO.Fe₂O₃**MAGNETITE****232***(Unit of calculation is the molecular proportion of FeO.)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.23	0.46	0.70	0.93	1.16	1.39	1.62	1.86	2.09
.01	2.32	2.55	2.78	3.02	3.25	3.48	3.71	3.94	4.18	4.41
.02	4.64	4.87	5.10	5.34	5.57	5.80	6.03	6.26	6.50	6.73
.03	6.96	7.19	7.42	7.66	7.89	8.12	8.35	8.58	8.82	9.05
.04	9.28	9.51	9.74	9.98	10.21	10.44	10.67	10.90	11.14	11.37
.05	11.60	11.83	12.06	12.30	12.53	12.76	12.99	13.22	13.46	13.69

Fe₂O₃**HEMATITE****160***(Unit of calculation is the molecular proportion of Fe₂O₃.)*

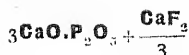
M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.16	0.32	0.48	0.64	0.80	0.96	1.12	1.28	1.44
.01	1.60	1.76	1.92	2.08	2.24	2.40	2.56	2.72	2.88	3.04
.02	3.20	3.36	3.52	3.68	3.84	4.00	4.16	4.32	4.48	4.64
.03	4.80	4.96	5.12	5.28	5.44	5.60	5.76	5.92	6.08	6.24

ZrO₂.SiO₂**ZIRCON****183***(Unit of calculation is the molecular proportion of ZrO₂.)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.18	0.37	0.55	0.73	0.91	1.10	1.28	1.46	1.65
.01	1.83	2.01	2.20	2.38	2.56	2.75	2.93	3.11	3.29	3.48
.02	3.66	3.84	4.03	4.21	4.39	4.58	4.76	4.94	5.12	5.31
.03	5.49	5.67	5.86	6.04	6.22	6.41	6.59	6.77	6.95	7.14

APPENDIX B

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APATITE

336

(Unit of calculation is the molecular proportion of P_2O_5 .)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.34	0.67	1.01	1.34	1.68	2.02	2.35	2.69	3.02
.01	3.36	3.70	4.03	4.37	4.70	5.04	5.38	5.71	6.05	6.38
.02	6.72	7.06	7.39	7.73	8.06	8.40	8.74	9.07	9.41	9.74
.03	10.08	10.42	10.75	11.09	11.42	11.76	12.10	12.43	12.77	13.10



TITANITE

196

(Unit of calculation is the molecular proportion of CaO .)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.20	0.39	0.59	0.78	0.98	1.18	1.37	1.57	1.76
.01	1.96	2.16	2.35	2.55	2.74	2.94	3.14	3.33	3.53	3.72
.02	3.92	4.12	4.31	4.51	4.70	4.90	5.10	5.29	5.49	5.68
.03	5.88	6.08	6.27	6.47	6.66	6.86	7.06	7.25	7.45	7.64



PEROVSKITE

136

(Unit of calculation is the molecular proportion of CaO .)

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.14	0.27	0.41	0.54	0.68	0.82	0.95	1.09	1.22
.01	1.36	1.50	1.63	1.77	1.90	2.04	2.18	2.31	2.45	2.58
.02	2.72	2.86	2.99	3.13	3.26	3.40	3.54	3.67	3.81	3.94
.03	4.08	4.22	4.35	4.49	4.62	4.76	4.90	5.03	5.17	5.30

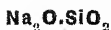


FLUORITE

78

(Unit of calculation is the molecular proportion of F_2 .)

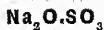
M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.07	0.16	0.23	0.31	0.39	0.47	0.55	0.62	0.70
.01	0.78	0.86	0.94	1.01	1.09	1.17	1.25	1.33	1.40	1.48
.02	1.56	1.64	1.72	1.79	1.87	1.95	2.03	2.11	2.18	2.26
.03	2.34	2.42	2.50	2.57	2.65	2.73	2.81	2.89	2.96	3.04

**CALCITE****100***(Multiply the molecular proportion by 100.)***SODIUM METASILICATE****122***(Unit of calculation is the molecular proportion of Na_2O .)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.12	0.24	0.37	0.49	0.61	0.73	0.85	0.98	1.10
.01	1.22	1.34	1.46	1.59	1.71	1.83	1.95	2.07	2.20	2.32
.02	2.44	2.56	2.68	2.81	2.93	3.05	3.17	3.29	3.42	3.54
.03	3.66	3.78	3.90	4.03	4.15	4.27	4.39	4.51	4.64	4.76

**HALITE****117***(Unit of calculation is the molecular proportion of Cl_2 .)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.12	0.23	0.35	7.47	0.59	0.70	0.82	0.94	1.05
.01	1.17	1.29	1.40	1.52	1.64	1.76	1.87	1.99	2.11	2.22
.02	2.34	2.46	2.57	2.69	2.81	2.93	3.04	3.16	3.28	3.39
.03	3.51	3.63	3.74	3.86	3.98	4.10	4.21	4.33	4.45	4.56

**THENARDITE****142***(Unit of calculation is the molecular proportion of SO_3 .)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.14	0.28	0.43	0.57	0.71	0.85	0.99	1.14	1.28
.01	1.42	1.56	1.70	1.85	1.99	2.13	2.27	2.41	2.56	2.70
.02	2.84	2.98	3.12	3.27	3.41	3.55	3.69	3.83	3.98	4.12
.03	4.26	4.40	4.54	4.69	4.83	4.97	5.11	5.25	5.40	5.54

**SODIUM CARBONATE****106***(Unit of calculation is the molecular proportion of CO_2 .)*

M.P.	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
.00	0.00	0.11	0.21	0.32	0.42	0.53	0.64	0.74	0.85	0.95
.01	1.07	1.17	1.27	1.38	1.48	1.59	1.70	1.80	1.91	2.01
.02	2.12	2.23	2.33	2.44	2.54	2.65	2.76	2.86	2.97	3.07
.03	3.18	3.29	3.39	3.50	3.60	3.71	3.82	3.92	4.03	4.13

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